COMPUTATION OF OPTIMUM PARAMETERS FOR COLD STORAGES

by

P. L. VENKATESH

DEPARTMENT OF MECHANICAL E
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR

CTOBER, 1984

DEDICATED

TO

MY PARENTS

CERTIFICATE

This is to certify that the thesis entitled " Computation of Optimum Parameters for Cold Storages" by P.L. VENKATESH is a record of work carried out under my supervision and has not been submitted elsewhere for a degree.

OCTOBER, 1984

MANOHAR PRASAD
ASSISTANT PROFESSOR
DEPT. OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY
KANPUR

ACKNOWLEDGEMENTS

I express my deep sense of gratitude to Dr. Manohar Prasad for his invaluable guidance and constant encouragement throughout the course of this work.

I am grateful to Dr. K.K. Saxena for his invaluable advice.

I am grateful to Mr. P.N. Misra for his technical and physical help.

I gratefully acknowledge Messrs United Refrigeration Works, Kanpur, for supplying the costs of various equipments.

Sincere thanks are due to my friends Shrinivas Umarji, Shantharam, Prasad, Madan, Bhowmick, Srinivas K and Shrirangachar for the valuable help rendered by them and their efforts to boost my spirit. I am also thankful to all my friends whose names could not be mentioned here.

I am thankful to Mr. D.P. Saini for his efficient typing of the thesis and Mr. B.K. Jain for his neat drawings.

VENKATESH, P.L.

CONTENTS

LIST OF FIGURES

NOMENCLATURE

a	length of the cold storage, m
b	breadth of the cold storage, m
c_1, c_{eff}, c_3, c_5	cost of insulation, Rs/m^3, electric charges, Rs./ton-h, cost of refrigerating machinery, Rs/ton-capacity, and digging and additional underground cost, Rs./m^3, respectively.
C_1 to C_5	cost of insulation, Rs./year, power cost, Rs./year, cost of refrigerating machinery, Rs./year, maintenance cost, Rs./year, digging and additional construction cost, Rs./year, respectively
C_{Total}	total cost, Rs./year.
F	factor for actual power consumption
H	height of the cold storage, m
h_i	inner heat transfer coefficient for vertical walls, kJ/m^{2}h°c
h_i'	inner heat transfer coefficient for ceiling, kJ/m^2 h°c
h_o	outside heat transfer coefficient, kJ/m^{2}h°c
h_o'	outside heat transfer coefficient for roof, kJ/m^{2}h°c
h_o''	equivalent heat transfer coefficient for underground soil resistance, kJ/m^2-h°c
I	interest rate per year
k	conductivity of main insulation kJ/mh°c
k_l	conductivity for the lth layer of wall above ground level, kJ/mh°c
k_j	conductivity for jth layer of wall below ground level, kJ/mh°c

k_m	conductivity for m^{th} layer of ceiling, kJ/mh°c
L	life of insulation and machinery, years
$\dot{Q}_{design}$	design heat load, kJ/h
$\dot{Q}_{actual}$	actual heat load, kJ/h
s	sink below ground level, m
S	safety factor for refrigeration system
ΔT_n	$T_{north} - T_{inside}$, °c
ΔT_s	$T_{south} - T_{inside}$, °c
ΔT_E	$T_{east} - T_{inside}$, °c
ΔT_W	$T_{west} - T_{inside}$, °c
ΔT_R	$T_{roof} - T_{inside}$, °c
T_{SE}	sol-air temp (eastern wall), °c
T_{SW}	sol-air temp. (western wall), °c
T_{SN}	sol-air temp. (northern wall), °c
T_{SS}	sol-air temp. (southern wall), °c
T_{SR}	sol-air temp. (roof), °c
ΔT_{SE}	$T_{SE} - T_{east}$, °c
ΔT_{SW}	$T_{SW} - T_{west}$, °c
ΔT_{SN}	$T_{SN} - T_{north}$, °c
ΔT_{SS}	$T_{SS} - T_{south}$, °c
ΔT_{SR}	$T_{SR} - T_{roof}$, °c
t	insulation thickness above ground level, m
t_1	insulation thickness below ground level, m
t_R	insulation thickness for roof, m

t_e	equivalent thickness for walls above ground level, m
t'_e	equivalent thickness for roof, m
t''_e	equivalent thickness for walls below ground level, m
U	overall heat transfer coefficient for walls above ground level, kJ/m^2-h-°c
U_D	overall heat transfer coefficient for walls below ground level, kJ/m^2-h-°c
U_R	overall heat transfer coefficient for roof, kJ/m^2-h-°c
V	volume of the cold storage, m^3

ABSTRACT

A generalized computer programme has been developed to optimize the insulation thickness, sink and dimensiôns of cold storage. The total cost comprising the initial and running costs based on the present worth method of economic analysis has been taken as the objective. Optimum insulation thickness has been determined for the ceiling and that part of the walls which is above and below ground level. The optimum sink to which the structure must be built, in order to minimize functional energy and cost, has also been determined.

Optimum length,breadth and height of the room have been determined for a given volume of the storage space.

Powell's method of unconstrained minimization coupled with the interior penalty function method to convert the constrained problem to the unconstrained one and the quadratic interpolation method are used in the optimization procedure.

Optimum insulation thickness has been determined for two types of insulating materials: Thermocole and Polystyrene foam insulation.

Optimum values of the design variables and the cost of the cold storage have been appraised for both cooling and freezing.

The vapour-compression refrigeration system using Ammonia as the working fluid has been selected in computing the cost of power needed for refrigeration.

Threlkeld's classical approach involving the concept of sol-air temperature has been made use of in calculating the cooling load on the system.

The variation of total cost with insulation thickness and sink has been studied for different dimensions, inside temperatures and different insulating materials.

Optimum values of the parameters determined by the hourly load calculation method has been compared with those obtained on the basis of standard design conditions.

The effect of orientation of the building,on optimum values of the parameters and the cost,has been studied.

The decrease in functional energy and the increase in total cost is studied for suboptimal solutions.

CHAPTER - 1

INTRODUCTION

1.1 DESCRIPTION

India, being mainly an agricultural country, produces large quantities of agricultural products of different varities. Some 20 to 30% of these products are wasted in the areas where they are grown, because of unavailability of a controlled environment. The estimated loss is about Rs. 1500 crores per year due to the perishing of these products [1].

Of the many perishable products the preservation of potatoes is the major application covering 80% of the cold stores in India [2]. The use of cold stores has been further diversified to store other commodities like fish and dairy products (5%), fruits, vegetables, flower, jaggery and other items (15%).

Cold storages maintain a low temperature and suitable humidity to prevent the spoilage of perishable products in one region and make them available in the off season as well as in other regions where they are not harvested. The growers also get a due share of the

profit by way of not selling their seasonal produce at throw away prices.

The rapid developments that are taking place in the cold storage industry, has led to greater importance being paid to the design aspect. Unlike the arbitrary design of earlier years, new vistas have been opened up in cold storage designs. The emphasis has been shifted to constructing cold storages and refrigerated warehouses with larger volumes, capable of storing a larger amount of commodities at a lesser cost. Improvements are being made in this field to minimise the functional energy requirements and the costs wherever possible.

Generally, a number of alternatives can be thought of for designing a new system or improving an existing one. In cold storages the structural cooling load, which is dependent on environment, is quite substantial apart from the commodity cooling load. The environmental parameters contributing to the structural cooling load are probabilistic and uncontrollable. Hence parameters like the thermal insulation, the area of the walls and the roof exposed to solar radiation and external environment, the orientation of the building, selection of design conditions and data, and the characteristics of the refrigerating system used for cooling are to be closely controlled in order to ensure optimum functional energy at lowest cost.

In this regard, energy saving can be achieved by decreasing the solar radiation falling on the walls and the roof of the cold store by sinking the structure partly or fully below the ground level, exposing lesser surface area to solar radiation. This also results in decreasing the infiltration heat load owing to the fact that heavier air stays in that part of the structure which is below ground level. Another advantage of sinking the structure partly or wholly under-ground is that the underground temperature of the soil is lower than the ambient temperature at any time of the day and moreover the underground temperature fluctuations with time is not as drastic as that of ambient temperature. Hence relatively more stable conditions prevail in partially underground storages imposing lesser transient load on the refrigeration system. Further, this system would serve a better purpose in places where electric breakdowns are frequent.

It is also seen that the insulation requirement for underground cold storages is considerably lower than that for cold storages which are above ground level, as a result of lesser heat transmission through underground walls.

The concept of an underground cold storage however has some disadvantages; like extra digging and underground constructional cost and unforeseen problems

due to seepage of water from the underground.

The shape and orientation of the structure also plays a vital role in energy saving. Since the west and east facing walls are subjected to longer exposures of solar radiation, the area of these walls should preferably be lesser than those of the north and south facing walls. Other orientations can be resorted to if it results in decreased structural cooling load and lesser costs. The best shape of the cold storage is that which renders minimum surface area for a given volume, rendering reduced cooling load and lesser insulation requirement. The shape of the cold storage is influenced by other practical problems like the constructional cost, maintenance and handling etc.

Lastly, energy saving can also be achieved by selecting proper refrigerating machinery and regular maintenance in order to achieve a high coefficient of performance.

In essence the optimum cold storage design is envisaged as having both financial feasibility and that functional energy which renders the overall cost for the cold storage a minimum.

1.2 LITERATURE REVIEW:

The work available in the field of design of refrigeration and air-conditioning systems pertaining to cold storages and refrigerated warehouses is summarized in the following paragraphs.

1.2.1 ANALYSIS OF COOLING LOAD CALCULATIONS AND HEAT TRANSFER THROUGH WALLS

The analysis of cooling load involves parameters such as the ambient air temperature, direct and diffused solar radiations, air velocity, characteristic of the enclosure walls and the orientation of the enclosure.

Threlkeld [3] has extensively described the process of heat transmission occurring through solid boundaries of a structure when a temperature differential exists between the internal and external environments. He has outlined a detailed procedure for the computation of solar irradiation on the walls and roof. Periodic heat transfer through the walls has been explicitly dealt with through the concept of sol-air temperature. His analysis essentially deals with heat transfer through homogeneous walls.

Mackey and Wright [4] have described in detail the periodic heat transfer through composite walls or roofs. They have also proposed conversion

equations to reduce a composite wall problem into that of an equivalent homogeneous wall. The following three methods have been developed to account for the periodicity of external conditions:

(i) Threlkeld's classical approach [3]

(ii) Transfer function method [5]

(iii) Finite difference method [6].

Threlkeld's classical approach involves the concept of sol-air temperature and is used in the present work.

In the transfer function method the various components of space heat gain are added together to get an instantaneous total rate of space heat gain, which is then converted into an instantaneous space cooling load through the use of weighting factors called coefficients of 'room transfer functions'. The transfer function is nothing more than a set of coefficients that relate an output function at a given time to the value of one or more driving functions at the time and previous times.

Kadambi and Hutchinson [6] have described an approximate technique to determine one dimensional transient heat transfer through walls and roofs, in the form of the Finite Difference method. The basic

simplicity of approximate method contrasted with analytical techniques is asserted in their work.

Probably, the best and most relevant description of cooling load calculations, from the point of view of practical designs, is outlined in ASHRAE, Handbook of Fundamentals [7]. The methodology and equations for hour-by-hour load calculations, used in the present work, is outlined in the handbook.

1.2.2 ECONOMICAL DESIGN AND OPTIMIZATION

With the limited availability of energy and its consequent increased cost, it has been necessary to use energy optimally. Extensive work has been done in minimizing the functional energy and cost of cold stores and refrigerated warehouses which are above ground level.

McClure [8] has described a method for the optimum design of building systems to reduce energy requirements.

Bonar [9] has analysed the different parameters and factors that affect the economics of a refrigeration system for a warehouse with reference to the minimization of total costs. Thermal insulation is found to be the foremost factor that affects the functional energy requirement and the energy cost as well.

Prasad [2] has provided a break up of the total cost of a cold storage as follows:

> building work (30%), steelwork and cladding (18%), refrigeration plant and electric (21%) and insulation (31%). Thus it can be seen that insulation alone accounts for about one thirds of the total cost. This gives a statistical picture as to the method of controlling the total overall cost of the whole system.

Spielvogel [10] has presented an interesting article as to how the use of more insulation than required can increase the energy consumption and cost.

Gupta [11] has done extensive work on automated optimum design of refrigerated warehouses and air conditioned buildings. He has formulated the design problem as a nonlinear mathematical programming problem and has used multidimensional optimization techniques to solve it. His work presents a probabilistic optimum design procedure by considering the randomness of the input parameters. He has used the approximate partial derivative method to evaluate the cooling or heating load. His work is an example of the application of extremal distributions in the optimum design of refrigeration and air conditioning systems.

Heinze [12] has made a comparative study of the single and multistoreyed cold storages, and the dependance of insulation thickness on storeyed constructions. Single storey cold storages are suitable for places where the cost of land is quite cheap, whereas multistorey cold storages are suitable to localities where land and labour are very costly. In such cases multistorey structures has been found to be more economical provided mechanical handling is used.

The work of Claesson and Holnquist [13] envisages the storage of cold and frozen food in underground mined rock caverns. Their work gives an idea of the energy saving from underground storage. They have suggested that such storages can be preferred where disused mines are readily available for underground construction.

Prasad et al [14], in an analytical study, have determined the expressions for optimum insulation thickness and sink of an underground cold storage in terms of various non-dimensional parameters. He has determined a quadratic relationship between the approximate optimum sink and insulation thickness. This paper forms the basis for the present work which determines optimum parameters, for a cold storage of any shape through iterative numerical method.

1.2.3 COMPUTER APPLICATIONS

Some years ago any extensive design analysis of air conditioning systems, in which computations were performed manually, was considered impractical. But with the advent of computers in the field of design such extensive design analysis has become very common.

ASHRAE [7] gives a methodology and equations for constructing computerized routines to duplicate results obtained with the tabular data, and to examine the effect of various systems and operating schedules on the space cooling load. Even though the speed of computations performed by a modern digital computer enables a rigorous approach to be formulated for calculating cooling loads, there are very few computer programs in use today where exact cooling loads are calculated.

Lokmanhekin and Henninger [15] have developed a comprehensive program that establishes cooling load requirements, energy estimating, equipment sizing, system simulation and economic analysis. Their program uses the advanced method of convolution principle to account for the thermal storage effect of a building. They have concluded that the convolution principle outlined in [16] gives more realistic values of peak loads and associated times of occurrence. An interesting feature

of their work is the thermal load plot which yields plots of the load profile of any space for any period of time. Comparison between plots permit grouping of compatible spaces into system control zones.

Evers [17] has developed a series of three computer programmes called the E cube series. These programmes compute the energy requirements, equipment selection and energy consumption and economic comparison. The energy requirement programme takes design point values for seven components of thermal load and the base component electrical load and distributes them over each hour of the year in accordance with dry-bulb and dew point temperature variations. The programme further evaluates the effects of thermostat setback or periodic system shutdown and thermal storage of any magnitude including temperature lag effects.

The equipment selection and energy consumption program determines the actual energy consumed by the various pieces of equipment used to meet the hourly requirements. The economic comparison programme is oriented towards making decisions concerning investments, annual operating costs and methods of financing.

1.3 PRESENT STUDY

The main design parameters considered in the present work are the insulation thickness for walls and ceiling, sink, length, breadth and height of the cold storage structure.

The design parameters of the cold storage have been optimized with respect to two cases:

1) Size of the cold storage being fixed

2) Volume of the storage space being fixed.

In the case where volume is assumed to be fixed the optimum dimensions of the building, such as length, breadth and height have been calculated. The volume of the cold storage is dependant on the quantity of commodity being stored.

The initial computations involve heat transfer through the structure and infilt ration heat load. The design heat load is computed on the basis of solar radiation during the hours from 10 AM. to 3 PM. However, the actual heat load is computed for the entire day. The concept of sol-air temperature has been used to compute heat loads.

These heat loads are used in computing the individual costs comprising both initial and running costs based on present worth analysis. Hence the total

cost per year which is the objective function in the optimization problem, is calculated. The objective function is minimized to achieve optimum values of the design parameters. The constraints on the design parameters are formulated on the basis of practical considerations. Both one dimensional graphic and mathematical programming techniques have been used to obtain optimum values.

In general the contributions of the present work can be stated as follows:

1) Development of automated optimization procedure for the design of cold storages.
2) Application of hourly weather data in the optimum design of such systems.
3) Analysis of the effect of sinking the structure below ground level.
4) Comparison of suitability of two different insulating materials.
5) Comparison of optimum parameters for two different orientations of the building.
6) Comparison of optimum parameters obtained by load calculations based on peak design conditions with those obtained by hourly load calculation.

In essence a generalized computer programme has been developed for the optimum design of cold storages and refrigerated warehouses.

The cost of electricity for calculating power charges was based on data from standard sources. A logistic curve was fitted through these past data to forecast the costs for future, in order to determine more realistic power cost charges per year by present worth method.

In order to generalize the program empirical relations for the properties of refrigerants, needed in the calculation of the coefficient of performance of the refrigeration system, are incorporated. These empirical relations depend only on the condenser and evaporator temperatures of the system. The evaporator temperature is selected on the requirements of inside temperature.

Lastly the feasibility of using a suboptimal design was studied, having larger insulation of the order of 20 to 30%.

CHAPTER - 2

PROBLEM FORMULATION

2.1 MATHEMATICAL MODELLING

2.1.1 DERIVATION OF EXPRESSIONS FOR COOLING LOAD

A cold storage can be of any shape like cubical or cuboidal. In order to generalise the derivation it is assumed that the cold storage is cuboidal in shape as shown in fig. 2.1.

Let the volume of the cold storage be V such that

$$V = a \cdot b \cdot H \tag{2-1}$$

where a,b and H are the length (along east-west), width and height respectively. The sink below the ground level is denoted by s.

The total heat-load is given by

$$Q = Q_1 + Q_2 + Q_{inf} + Q_{fixed} \tag{2-2}$$

where Q_1 and Q_2 are heat transfer rates above and below the ground level respectively. Q_{inf} is the infiltration heat load and Q_{fixed} is the fixed heat load, that is independent of the insulation thickness, sink and the dimensions of the cold storage.

The heat transfer rate above the ground level is given by:

$$Q_1 = U \cdot a \cdot (H-s) \left[\Sigma \Delta T_n + \Sigma \Delta T_s + \Sigma \Delta T_{SS} + \Sigma\Delta T_{SN}\right]$$
$$+ U \cdot b(H-s) \left[\Sigma \Delta T_E + \Sigma \Delta T_{SE} + \Sigma \Delta T_W + \Sigma \Delta T_{SW}\right]$$
$$+ U_{roof} \cdot a \cdot b \left[\Sigma \Delta T_R + \Sigma \Delta T_{SR}\right] \qquad (2-3)$$

Here T_{SE}, T_{SS}, T_{SW} and T_{SR} are the magnitudes of the temperature above ambient value to account for the radiation effects (sol-air temperature) [3] , for the Eastern, Southern, Western sides and the roof respectively.

$$\Delta T_{SS} = T_{SS} - T_S \qquad (2-4a)$$

$$\Delta T_{SE} = T_{SE} - T_E \qquad (2-4b)$$

$$\Delta T_{SW} = T_{SW} - T_W \qquad (2-4c)$$

$$\Delta T_{SR} = T_{SR} - T_R \qquad (2-4d)$$

The overall heat transfer coefficients are given by

$$U = \frac{1}{\left[\frac{1}{h_i} + \frac{1}{h_o} + \frac{t}{k} + \sum_{t=1}^{n} ({t_1}/{k_1})\right]} = \frac{k}{t + t_e} \qquad (2-5)$$

and,

$$U_{roof} = \frac{1}{\left[\frac{1}{h_i'} + \frac{1}{h_o'} + \frac{t_R}{k} + \sum_{m=1}^{n}\left(\frac{t_m}{k_m}\right)\right]} = \frac{k}{t_R + t_e'} \qquad (2-6)$$

where t_e and t_e' are equivalent thickness for the

n-layered walls and n′ layered roof, respectively.

The thickness of the main insulation and the conductivity are t and k., respectively.

Therefore,

$$Q_1 = \frac{k}{(t+t_e)} (H-s) \left[a \{ \Sigma \Delta T_n + \Sigma \Delta T_s + \Sigma \Delta T_{SS} + \Sigma \Delta T_{SN} \} + b \{ \Sigma \Delta T_E + \Sigma \Delta T_{SE} + \Sigma \Delta T_U \} + \Sigma \Delta T_{SW} \right]$$

$$+ \frac{k}{(t_R + t_e')} \cdot a \cdot b \left[\Sigma \Delta T_R + \Sigma \Delta T_{SR} \right] \qquad (2\text{-}7)$$

The heat load for the underground structure is calculated as:

$$Q_2 = U_D \, 2 \, (a + b) \, S \, \Sigma \Delta T_1 \qquad (2\text{-}8)$$

where U_D is given by

$$U_D = \frac{1}{\left[\frac{1}{h_i''} + \frac{1}{h_o''} + \sum_{j=1}^{n''} \left(\frac{t_j}{k_j} \right) + \frac{t_1}{k} \right]} = \frac{k}{t_1 + t_e''} \quad \ldots \qquad (2\text{-}9)$$

The magnitude of h_o'' for the underground structure is assigned to be 2 k J m^2h °k based on practical considerations [13].

The quantity ΔT_1 is calculated from the underground temperature data [19].

Thus $$\dot{Q}_2 = \frac{k}{t_1+t_e} 2 \ (a + b) \ S \ \Sigma \Delta T_1 \qquad (2\text{-}10)$$

The infiltration heat load is given by

$$\dot{Q}_{inf} = \frac{a \cdot b \ (H-s)}{v_a} \ \frac{\eta_{ch}}{24} \ \Sigma \ (h_a - h_i) \qquad (2\text{-}11)$$

where η_{ch} is the number of air changes per day given by the empirical relation

$$\eta_{ch} = 110.08 - 54.8906 \ln (V) + 11.426 \ [\ln(V)]^2 - 11.32 \ [\ln(V)]^3 + 0.043708 \ [\ln(V)]^4$$

$$\ldots\ldots \qquad (2\text{-}12)$$

h_a, h_i are the enthalpies of the ambient air and inside air respectively.

The design heat load is then given by

$$\dot{Q}_{des} = \dot{Q}_1 + \dot{Q}_{inf} + \dot{Q}_2 \qquad (2\text{-}13)$$

Over the peak load hours i.e. 10 a.m. to 3 p.m.

$$\dot{Q}_{des} = 1.1 \Big[\frac{k}{(t+t_e)} \ (H-s) \Big\{ a \Big(\sum_{10am.}^{3pm.} \Delta T_n + \sum_{10am.}^{3pm.} \Delta T_S + \sum_{10am.}^{3pm.} \Delta T_{SN} + \sum_{10am.}^{3pm.} \Delta T_{SS} \Big)$$

$$+ b \Big(\sum_{10am.}^{3pm.} \Delta T_E + \sum_{10am.}^{3pm.} \Delta T_{SE} + \sum_{10am.}^{3pm.} \Delta T_W + \sum_{10am.}^{3pm.} \Delta T_{SW} \Big) \Big\}$$

$$+ \frac{k}{(t_R+t_e)} \ a \cdot b \cdot \Big[\sum_{10am.}^{3pm.} \Delta T_R + \sum_{10am.}^{3pm.} \Delta T_{SR} \Big]$$

eqn. contd.

$$+ \frac{k}{(t_1+t_e'')} 2 (a + b) s \sum_{10am.}^{3pm.} \Delta T_1$$

$$+ \frac{a \cdot b (H-s)}{v_a} \frac{\eta_{ch}}{24} \sum_{10am.}^{3pm.} (h_a - h_i)] \quad (2-14)$$

Q_{fixed} has not been considered here because it is independent of t, t_R , t_1 , a, b, H and s.

The factor 1.1 has been incorporated in the above equation to account for the heat transfer through the floor [20].

The tonnage of the refrigerating system having SF as a safety factor is given by

$$T_R = \frac{SF \ Q_{des}}{12,600 \times 5} \quad (2-15)$$

The actual heat load is given by

$$Q_{act} = 1.1 [\frac{k}{(t+t_e)} (H-s) \{ a (\sum_{24hrs.} \Delta T_n + \sum_{24hrs.} \Delta T_S$$

$$+ \sum_{24hrs} \Delta T_{SN} + \sum_{24hrs.} \Delta T_{SS})$$

$$+ b (\sum_{24hrs.} \Delta T_E + \sum_{24hrs.} \Delta T_{SE} + \sum_{24hrs.} \Delta T_W$$

$$+ \sum_{24hrs.} \Delta T_{SW}) \}$$

$$+ \frac{k}{(t_R + t_e')} a \cdot b \{ \sum_{24hrs.} \Delta T_R + \sum_{24hrs.} \Delta T_{SR} \}$$

$$+ \frac{k}{(t_1 + t_e'')} 2 (a+b) s \sum_{24hrs.} \Delta T_1$$

eqn. contd.

$$+ \frac{a \cdot b\,(H - s)}{v_a} \quad \frac{q_{ch}}{24} \sum_{24h} (h_a - h_i)] \qquad (2\text{-}16)$$

2.1.2 HEAT TRANSFER BY SOLAR RADIATION

In the problem of heat transfer through walls and roof, the two principal factors of the external thermal environment are the out door air temperature and solar radiation intensity. Both are subjected to erratic fluctuations of which the former follows essentially a periodic variation on clear days. In the present analysis, a constant internal thermal environment and periodic variations of out door air temperature and solar radiation intensity are considered.

Figure 2.2 shows a diurnal variation in out door air temperature for Kanpur city during a typically hot day in June. It can be observed that minimum temperature usually occurs just before sunrise while maximum temperature usually occurs some 1 to 3 hours after the solar noon.

Figure 2.3 exhibits the variation in direct solar radiation over the day. It can be seen that the direct solar radiation reaches a maximum at solar noon and exists only during sunrise to sunset.

2.1.3 INCIDENT SOLAR RADIATION

The total radiation, I_t reaching a terrestrial surface is the sum of the direct solar radiation I_D , the diffuse sky radiation I_d , and the solar radiation reflected from the surrounding surface I_r.

The intensity of the direct component is the product of the direct normal irradiation I_{DN} , and the cosine of the angle of incidence θ, between the incoming solar rays and a line normal to the surface, Fig. 2.3.

Thus,

$$I_t = I_{DN} \cos \theta + I_d + I_r \ \mathrm{W/m^2} \qquad (2\text{-}17)$$

In the present analysis the reflected radiation is neglected.

2.1.3.1 DIRECT NORMAL SOLAR INTENSITY

At the earth's surface on a clear day I_{DN} is represented by,

$$I_{DN} = \frac{A}{\exp(B/\sin \beta)} \ \mathrm{W/m^2} \qquad (2\text{-}18)$$

where 'A' is the apparent solar irradiation at air mass equal to zero and 'B' is the atmospheric extinction coefficient tabulated in [7].

2.1.3.2 DIFFUSE SOLAR RADIATION

The diffuse radiation falling on any surface consists of radiation from the sky and part of the reflected solar radiation from adjacent surfaces, particularly the ground lying south of the surface in question. A simplified general relation for the diffuse solar radiation I_{DS} from a clear sky that falls on any surface is given approximately by the following equation:

$$I_{DS} = C \, I_{DN} \, F_{SS} \quad W/m^2 \tag{2-19}$$

where 'C' the diffuse radiation factor, is tabulated in [7] and F_{SS} is the angle factor between the surface and the sky. F_{SS} is 0.5 for vertical surfaces and 1.0 for horizontal surfaces.

2.1.4 DETERMINATION OF SOLAR ANGLES

The sun's position in the sky can be most conveniently expressed in terms of solar altitude β, above the horizontal, and the solar azimuth ϕ, measured from the south. These angles β and ϕ depend on the latitude of the place L ; the solar declination δ , which is a function of the date and hour angle h.

The following equations relate β and ϕ to the three angles mentioned above

$$\sin \beta = \cos L \cos \delta \cos h + \sin L \sin \delta \qquad \text{....(2-20)}$$

$$\cos \phi = (\sin \beta \sin L - \sin \delta)/(\cos \beta \cos L) \qquad \ldots \quad (2\text{-}21)$$

The hour angle is zero degree at solar noon and increases by $(360/24)^{\circ}$ every hour.

The value of solar declination as a function of date is tabulated in [7].

The solar position angles and incident angles for horizontal and vertical surfaces are shown in fig. 2.4, where line OQ leads to the sun, the north-south line is SON and the east-west line is EOW, line OV is perpendicular to the horizontal plane in which the solar azimuth, angle HOS(ϕ), and the surface azimuth, angle POS(Ψ) are located. The surface solar azimuth (r) is the angle HOP. The angle of incidence θ for any surface is defined as the angle between the incoming solar rays and a line normal to that surface. For the horizontal surface in fig. 2.4, the incident angle θ_H is QOV; for the vertical surface the incident angle θ_V is QOP.

For any surface incident angle 'θ' is related to β, r and the tilt angle of the surface ν by

$$\cos \theta = \cos \beta \cos r \sin \nu + \sin \beta \cos \nu \qquad \ldots \quad (2\text{-}22)$$

when the surface is horizontal $\nu = 0$, and

$$\cos \theta_H = \sin \beta \qquad (2\text{-}23)$$

For a vertical surface, $\nu = 90°$ and

$$\cos \theta_V = \cos \beta \cos r \qquad (2\text{-}24)$$

2.1.5 OUTSIDE HEAT TRANSFER COEFFICIENT

The evaluation of summer thermal load for a given structure requires knowledge of each of the thermal resistance interposed between inside contained atmosphere and outside air. One such resistance is that of the film adjacent to the outside surface.

By common usage this outside combined (radiation plus convection) film coefficient is taken as 122.7 kJ/m^2-for summer [6]. The above standard film coefficients are reasonable average values and their use permits tabulation of overall coefficients of heat transmission for a multitude of types of construction. However it should be recognised that, in particular localities there is a marked variation from the standard value. This section presents a simple tabular method for obtaining a design value of the outside heat transfer coefficient as a function of local climatological conditions, and correcting the " standard " values so that they will be more precisely applicable to different locations.

h_o is given by the following empirical relations.

For very smooth, smooth, moderately rough and rough surfaces h_o is respectively given by,

$$h_o = 14.278 + 3.559\ V_{wind} \qquad (2.25a)$$

$$h_o = 13.423 + 3.31\ V_{wind} \qquad (2.25b)$$

$$h_o = 26.55 + 5.0663\ V_{wind} \qquad (2.25c)$$

$$h_o = 23.64 + 6.364\ V_{wind} \qquad (2.25d)$$

in kJ/m^2-h-°c when V_{wind} is given by km/h.

2.1.6 CALCULATION OF SOL-AIR TEMPERATURE

In heat transmission calculations, it is convenient to combine the effects of outdoor air temperature and solar radiation intensity into a single quantity. The rate of heat transfer q_o from the external thermal environment to the outside surface of a sunlit wall or roof may be written as

$$q_o = h_o\ (T_o - T_{w,o}) + \alpha_s I \qquad (2\text{-}26)$$

where T_o is the temperature of the outdoor air, $T_{w,o}$ is the temperature of the outside wall surface, α_s is the solar absorptivity of the wall, and I is the combined incidence of solar radiation (direct and diffuse) upon the surface. The rate of heat transfer q_o may be expressed as

$$q_o = h_o\ (T_e - T_{w,o}) \qquad (2\text{-}27)$$

From Eqns. (2-26) and (2-27), one gets

$$T_e = T_o + \alpha \, I/h_o \qquad (2\text{-}28)$$

This fictitious temperature T_e is called sol-air temperature.

The variations of sol-air temperature with time may be assumed to be repetitive for successive 24 hour cycles. Any of the curve may be mathematically expressed in terms of a Fourier series. Thus if $T_e = f(\theta)$, where θ is the number of hours measured from midnight solar time, we have

$$T_e = T_{e,m} + M_1 \cos \omega_1\theta + N_1 \sin \omega_1\theta + M_2 \cos \omega_2\theta + N_2 \sin \omega_2\theta + \ldots.. \qquad (2.29)$$

where the coefficients $T_{e,m}$, M_n and N_n are given by

$$T_{e,m} = \frac{1}{24} \int_o^{24} T_e \, d\theta \qquad (2\text{-}30)$$

$$M_n = \frac{1}{12} \int_o^{24} T_e \cos \omega_n\theta \, d\theta \qquad (2\text{-}31)$$

$$N_n = \frac{1}{12} \int_o^{24} T_e \sin \omega_n\theta \, d\theta \qquad (2\text{-}32)$$

where $\omega_1 = \pi/12$ radians per hour and $\omega_n = n\omega_1$.

2.1.7 INFILTRATION LOAD

Infiltration load is due to the air that leaks into the conditioned space from the surroundings are viceversa. The exact estimation of the leakage of air

through apertures is extremely difficult. However, approximate values have been tabulated by ASHRAE [7]. Similarly the leakage of air due to door openings and through shutters is also based on practical experience in terms of the room sizes. The volume of infiltrated air is related with the volume of the room for different usages - average usage, long usage and heavy usage. The infiltration heat load is already described by equation (2-11).

2.1.8 HEAT TRANSFER THROUGH THE STRUCTURE

The heat transferred through a multilayered structure of a system having N layers from the outside environment to the inside is given by

$$Q = UA\ (T_a - T_i) \tag{2-33}$$

where U is the overall heat transfer coefficient given by

$$\frac{1}{U} = \frac{1}{h_i} + \sum_{i=1}^{N} \frac{t_i}{k_i} + \frac{1}{h_o} + \frac{t}{k} \tag{2-34}$$

where t is the insulation thickness and k is the conductivity of the insulation material. T_a and T_i are the ambient and inside temperatures, respectively. A is the area of the wall through which heat is being transferred.

h_i , the inside heat transfer coefficient is a function of the temperature drop across the film formed over the wall surface. h_i is given by the following empirical relations [6]

$$h_i = 5.598 \; (\Delta T)^{0.25} \tag{2-35a}$$

for floor $h_i = 6.0276 \; (\Delta T)^{1/3}$ (2-35b)

for the ceiling

where h_i is in kJ/m^2-h-°c and

$$\Delta T = (T_{wi} - T_i) \tag{2-36}$$

The above equation for h_i cannot be solved directly, since in such case the film coefficient is a function of ΔT across the film, and ΔT is itself a function of the film coefficient. An iterative trial and error procedure is therefore necessary.

2.2 ECONOMIC MODELS

The following four economic models are generally considered in the analysis of any investment policy. Any of them can be used to indicate the most favourable choice amongst several alternatives. Some of the merits and demerits of the same are briefly discussed.

2.2.1 PRESENT WORTH METHOD

In this method all the costs are transferred into the present worth. In order to determine the present worth of a future sum , the interest rate is established first. Then present worth is the value of a sum of money at the present time that, with compounded interest, will have a specified value at a certain time in future. Thus

$$P = \frac{S}{(1+r)^n} = (PWF)\ S \qquad (2-37)$$

where P = principal

r = rate of interest per period

S = total amount to be repaid at future time

n = number of periods

PWF = single paayment present worth factor.

The series present worth is given by

$$P = R \left[\frac{(1+r)^n - 1}{r(1+r)^n} \right] = (R)\ (SPWF) \qquad (2-38)$$

where P = original amount

R = amount withdrawn at the end of first and subsequent periods and

SPWF = series present worth factor.

Although the present worth method is most widely used, it presents some difficulty if the life times of two possible investments are different.

2.2.2 ANNUAL COST METHOD

It transforms all non-annual costs to an annual basis. In this method also the rate of interest must be established first.

$$R = P\left[\frac{r(1+r)^n}{(1+r)^n-1}\right] = P\ (CRF) \qquad (2\text{-}39)$$

where CRF is the annual recovering factor.
The annual cost method has two advantages over the present worth method. One is that there is no complication introduced when the prospective investments have different lives. The second is that it is more natural for most people to think in terms of an annual cost than in terms of the present worth.

2.2.3 RATE OF RETURN METHOD

In this method no assumption is made regarding the interest rate. Instead the money for the investment is considered to be in hand, and the rate of return is calculated as though it were an interest rate received by making an outside investment. Here we find r such that

P (CRF) - solvage value (SFF) = Net income

where SFF = Sinking fund factor $= \left[\frac{r}{(1+r)^n-1}\right]$ (2-40)

2.2.4 BREAK EVEN POINT

This method assumes that money is borrowed at a specific rate of interest and that the loan is paid off as rapidly as possible with no profits extracted. The break even point is defined as the time where the loan is paid off and profits begin following to the investor. In contrast to the rate of return method where the interest rate was unknown, the life is unknown in this method. Thus one finds n such that

$$P(CRF) - \text{Salvage value } (SFF) = \text{Net income} \qquad .. \quad (2\text{-}41)$$

2.2.5 ANNUAL COST WITH SIMPLE INTEREST

A simple economic model of annual cost with simple interest instead of compound interest can also be considered. Here

$$R = \frac{P\ (1 + nr)}{n} \qquad (2.42)$$

In the present work, the present worth method is considered to decide about the investment policy for the optimization problem.

2.2.6 COST ANALYSIS

The various individual costs which contribute to the total cost in terms of present worth follows:

(1) COST OF INSULATION FOR WHOLE STRUCTURE:

$$C_1 = \frac{c_1[2(H-s)\ (a+b)\ t + 2s(a+b)\ t_1 + a\ b\ (t_1 + t_R)]}{L} \quad \ldots \quad (2-43)$$

where c_1 is the cost of insulation per unit volume and L is the life of machinery and insulation.

(2) COST OF POWER:

$$C_2 = \frac{c_{eff}\ \dot{Q}_{actual} \times 365}{12,600} \cdot \frac{3.5}{COP} \cdot F \qquad (2-44)$$

where $$c_{eff} = \frac{1}{L} \sum_{i=1}^{L} \frac{c_{e_i}}{(1 + R)^{i-1}} \qquad (2-45)$$

c_{e_i} is the cost of electricity for the i^{th} year (Appendix - B). c_{eff} is the effective cost of electricity (Rs/KWH). F is a factor for the actual power consumption of the system per year. R is the rate of interest.

(3) COST OF REFRIGERATING MACHINERY:

$$C_3 = \frac{c_3 \cdot SF\ \dot{Q}_{design}}{5 \times 12,600 \times L} \qquad (2-46)$$

where c_3 is the cost of refrigerating machinery per ton capacity. SF is the safety factor for refrigerating machinery.

(4) MAINTENANCE COST:

$$C_4 = (0.10)\ c_5 \left[\frac{(1 + R)^L - 1}{R(1 + R)^{L-1}} \right] \qquad (2\text{-}47)$$

maintenance cost has been considered as 10% of the equipment cost [20].

(5) DIGGING AND ADDITIONAL UNDERGROUND CONSTRUCTION COST:

$$C_5 = c_5\ (s \cdot a \cdot b) \qquad (2\text{-}48)$$

where c_5 is the digging and additional cost for the structure per unit volume.

The total cost per year is then given by

$$C_{TOTAL} = \sum_{i=1}^{5} C_i \qquad (2\text{-}49)$$

CHAPTER - 3

OPTIMIZATION

3.1 TERMINOLOGY AND STATEMENT OF THE PROBLEM

Optimization is the process of determining the best results under the given circumstances.

The optimization problem is stated as follows:

Find $X = \{ x_1 , x_2 , \ldots\ldots x_n \}$ (3-1)

which minimizes f(X) subject to the constraints

$$g_j(X) \leq 0 \, , \; j = 1,2,\ldots,m \qquad (3\text{-}2a)$$

and $$l_j(X) = 0 \, , \; j = m+1, m+2,\ldots,p \qquad (3\text{-}2b)$$

where X is an n-dimensional vector called the design vector, f(X) is called the objective function and $g_j(X)$ and $l_j(X)$ are the inequality and the equality constraints, respectively.

The design vector describes a set of quantities of an engineering system which are viewed as variables during the design process. The design variables are collectively represented as a design vector

$$X = \{ x_1 , x_2 , \ldots\ldots x_n \} \qquad (3\text{-}3)$$

In practical problems, the design variables cannot be chosen arbitrarily, instead they have to satisfy certain conditions and requirements. The restrictions that are placed on the design variables in order to achieve an acceptable design are called design constraints.

It can be seen that in most engineering design procedures there exists more than one acceptable design. Since the purpose of optimization is to choose the best out of the many designs,a criterion has to be chosen for comparing the different alternate acceptable designs and selecting the best one. This criterion with respect to which the design is optimized, when expressed as a function of the design variables is known as 'objective function'.

In the present study the objective function is the total average annual cost of the cold storage which comprises the initial and running costs based on the present worth method. The design variables are the thickness of insulation on the walls above the ground level and on the ceiling, the sink (depth below ground level of the building) and the length and breadth of the cold storage structure. The insulation thickness for that part of the walls which is below ground level is taken as some fraction of the optimum insulation thickness for that part above the ground. The height of the cold

storage structure is a function of the length and breadth for a given volume.

Thus our object is to determine the insulation thickness, sink and the dimensions of the structure in such a way that the average annual total cost is minimum.

The constraints on insulation thickness are characterised by the form in which the thermal insulation panels are available in the market. Some insulants like corkboard and polystyrene foam are available in sheets of standard thickness while other insulant like glass-wool is available in loose form and has to be compacted into sheets or slabs.

The constraint on the sink is governed by the fact that the sink has to be positive and that it cannot exceed the height of the structure. The extreme conditions are the whole building being above or below ground-level.

The constraints on the dimensions of the cold storage depend on the volume of the cold storage and on the fact that volume is in itself governed by the amount and specific volume of the stored commodity. The maximum length of the cold storage is limited from the point of view of handling and good air distribution. The height of the cold storage is decided from the height of each

pallet and the number of pallets to be stacked. Additional height for safety, manoeuvring and air distribution is also accounted.

With these considerations the height of structure may vary from 6 to 15 m and the width varies from 15 to 25 m.

3.2 OBJECTIVE FUNCTION

In the present study the objective function is the average annual cost for the entire life span of the insulation and machinery in terms of the present value. The average annual cost comprises both the initial and running costs.

The optimization procedure is independent of the fixed heat load and hence the fixed costs. Fixed load takes into account the heat load from the stored commodity, heat generated inside the conditioned space and ventilation heat load.

It can be seen that the optimization variables like insulation thickness, sink or dimensions of the room do not influence the fixed load and hence the fixed cost. In this regard the objective function does not comprise the fixed cost.

The various individual costs incurred (in terms of the present value) over the entire life span of L years have been divided by L to compute the objective function.

The initial cost comprises the cost of insulation, the cost of machinery for refrigeration, the cost of digging and underground constructional cost. The running cost comprises the cost of power (electricity) and the cost of maintenance.

The cost of refrigerating machinery is a function of the tonnage for the required system. The tonnage of the system is given by

$$TR = \frac{SF \cdot \dot{Q}_{design}}{12,600 \times 5} \text{ tons} \tag{3-4}$$

where $\dot{Q}_{design}$ is the design heat load for five hours from 10 AM to 3 PM.

The cost of power is a function of the actual heat load ($\dot{Q}_{actual}$) for 24 hours and the coefficient of performance of the system.

The maintenance cost is assumed to be 10% of the cost of refrigerating machinery [20].

The cost of insulation and digging are functions of the dimensions of the cold storage.

The objective function is the average annual cost being expressed as the present worth of all the

expenditures.

$$f(X) = C_{initial} + C_{running}$$
$$= (C_1 + C_3 + C_5) + (C_2 + C_4) \qquad (3\text{-}5)$$

The functional dependence of the objective function is expressed as

$$\text{Average Annual Cost} = f\ (t, t_R, t_1, a, b, H, s) + g(\text{constants}) \qquad (3\text{-}6)$$

Our object is to minimize this average annual cost by varying t, t_R, a, b and s subject to constraints.

3.3 OPTIMIZATION TECHNIQUE

An optimization problem in which there is no restriction on the choice of the design vector, is called an unconstrained optimization problem. Any restriction on the design vector constitutes what is called the constrained optimization problem. Most of the problems in engineering applications are constrained, but some of the most powerful and convenient methods of solving constrained problems involve the conversion of the constrained problem to one of unconstrained minimization and this technique has been used in the present work.

3.3.1 THE UNCONSTRAINED MINIMIZATION TECHNIQUE

The multidimensional unconstrained minimization technique being used in the present work is the Powell's

conjugate direction method.

Detailed description of this method is available in any standard text on optimization [21].

In this method at each point in the function space under consideration, there is a preferred direction along which the values of the design variables are changed systematically by a well defined scheme, which leads to the minimum. Thus starting from the initial guess one arrives at the minimum through the sequence of improved approximations, each derived from the previous approximation. The Powell's method is a non-gradient method and it has the property of quadratic convergence. Without going into any mathematical detail a brief description of the algorithm is presented here.

3.3.2 POWELL'S METHOD

It is an extension of the idea of pattern move. For an intuitive understanding, Fox [22] describes the method as follows: Given that the function has been minimized once in each of the co-ordinate directions and then in the associated pattern direction, discard one of the co-ordinate directions in favour of the pattern direction for inclusion in the next m minimizations, since this is likely to be a better direction than the discarded one. After the next cycle of minimizations,

generate a new pattern direction and again replace one of the co-ordinate directions. Fig. 3.1 explains the algorithm. The basic method has a tendency to choose nearly dependant direction in ill-conditioned problems and the method may fail to converge to the actual minimum. One simple remedy is to reset the directions to the original co-ordinate vectors periodically and whenever there is some indication that the directions are no longer productive Powell has recommended a more effective procedure to overcome this difficulty [23]. The search is terminated when the relative change in the function value and in all the design variables, between two consecutive cycles of minimization, is less than the desired accuracy.

3.3.3 QUADRATIC INTERPOLATION

In this technique the function $F(\alpha)$ is approximated by a function $H(\alpha)$ which has an easily determinable minimum point. $H(\alpha)$ is expressed as

$$H(\alpha) = a + b\alpha + c\alpha^2 \qquad (3\text{-}7)$$

the minimum of which occurs at

$$\frac{dH}{d\alpha} = b + 2c\alpha = 0 \qquad (3\text{-}8)$$

or

$$\alpha^* = - b/2c \qquad (3\text{-}9)$$

The constants a, b and c for the approximating quadratic can be determined by sampling the function at three different α values, α_1 , α_2 and α_3 and solving the

equations

$$F_1 = a + b\alpha_1 + c\alpha_1^2 \tag{3-10}$$

$$F_2 = a + b\alpha_2 + c\alpha_2^2 \tag{3-11}$$

and
$$F_3 = a + b\alpha_3 + c\alpha_3^2 \tag{3-12}$$

where F_1 , F_2 and F_3 stand for $F(\alpha_1)$, $F(\alpha_2)$ and $F(\alpha_3)$ respectively.

Solving the above three equations, the values of a, b, c and α^* are obtained as

$$c = \frac{[(F_3-F_1)\ (\alpha_2-\alpha_1) - (F_2-F_1)\ (\alpha_3-\alpha_1)]}{[(\alpha_1-\alpha_2)\ (\alpha_2-\alpha_3)\ (\alpha_3-\alpha_1)]} \quad \ldots \tag{3-13}$$

$$b = (F_2-F_1)/(\alpha_2-\alpha_1) - c(\alpha_2+\alpha_1) \tag{3-14}$$

$$a = F_1-b\alpha_1-c\alpha_1^2 \tag{3-15}$$

$$\alpha^* = \frac{-b}{2c} \tag{3-16}$$

Choosing a, r and 2r for α_1 , α_2 and α_3 respectively, where r is the preselected trial step-length. One obtains

$$a = F_1 \quad \ldots\ldots\ldots\ldots \tag{3-17}$$

$$b = (4F_2 - 3F_1 - F_3)\ /\ 2r \tag{3-18}$$

$$c = (F_3 + F_1 - 2F_2)\ /\ 2r^2 \tag{3-19}$$

and
$$\alpha^* = \frac{(4F_2 - 3F_1 - F_3)}{(4F_2 - 2F_3 - 2F_1)} \tag{3-20}$$

For α^* to correspond a **minimum** for $H(\alpha)$, it must satisfy

$$\left.\frac{d^2H}{d\alpha^2}\right|_{\alpha=\alpha^*} > 0 \qquad (3\text{-}21)$$

Since H is a quadratic, this requires $c > 0$ or $(F_3 + F_1) > 2F_2$.

The point α^* is considered to be a sufficiently good approximation to the minimum of $F(\alpha)$ if

$$\frac{H(\alpha^*) - F(\alpha^*)}{F(\alpha^*)} \leq \varepsilon \qquad (3\text{-}22)$$

where ε is a small number to be specified depending on the accuracy desired. Fig. 3.2 explains the algorithm.

3.3.4 THE PENALTY FUNCTION METHOD

The basic function of the interior penalty function method is to convert the original constrained problem into one of unconstrained minimization by blending the constraints into a composite function and making it possible to ignore them at the minimization stage. In this method the numerical solutions are sought by solving a sequence of unconstrained minimization problems.

The advantage of penalty function method is that;powerful, well studied and reliable algorithms for the unconstrained minimization of arbitrary functions can be used in this method.

The penalty function formulations for inequality constrained problems can be divided into two categories; interior and exterior. In the interior formulation, the unconstrained minima lie in the feasible region and converge to the solution as a special parameter is varied. In the exterior formulations, they lie in the infeasible region and converge to the solution from the outside.

The advantage of the interior penalty function method is that, given an initial acceptable, it produces an improving sequence of acceptable decisions. Moreover, we approach the constraints in such a way that they become critical only near the end. This is a desirable feature in engineering design because one is free to choose a suboptimal but less critical design if required.

After studying the relative advantages and disadvantages of the available methods, the interior penalty function is used in the present work.

In the interior penalty function method a new function (Ø function) is constructed by augumenting a penalty term to the objective function. The Ø function is defined as

$$\emptyset\,(D, r_k) = F(D) - r_k \sum_{j=1}^{m} \frac{1}{g_j(D)} \qquad (3\text{-}23)$$

where F is to be minimized over all D satisfying

$$g_j(D) \leq 0 \; , \; j = 1,2,\ldots.m \tag{3-24}$$

The penalty parameter r is made successively smaller in order to obtain the constrained minimum of F.

The flow diagram of fig. 3.3 explains the algorithm.

The interior penalty function method requires a feasible starting point for the search towards the optimum point. In cases where finding a feasible starting point is difficult, the penalty function method itself can be used for finding it, but the procedure is time-consuming.

CHAPTER - 4

RESULTS AND DISCUSSIONS

4.1 COMPUTATIONAL METHOD

The objective function formulated in Chapter 2 has been optimized, as outlined in Chapter 3, for various inside temperatures and insulation material.

An Ammonia Vapour-Compression refrigeration system has been considered for the necessary cooling of the cold storage space. Life of the insulation and the refrigerating system have been taken as 20 years and an operating factor of 0.75 for power consumption has been considered. A condenser temperature of 42°c and evaporator temperature of - 3°c have been assumed. Further it has been assumed that the refrigerant is being superheated by 5°c and undercooled by 5°c. Under these conditions, the coefficient of performance of the system turns out to be 3.5511. Empirical relations for refrigerant properties are given in Appendix-A.

A method to compute the present worth effective electricity charges by forecasting future electricity costs is discussed in Appendix-B [24].

A computer programme was made, based on mathematical formulation, having a generalized approach and realistic methods. The formulation deals with two cases:

(i) Determination of optimum insulation requirement for a given size of the cold storage and

(ii) Determination of optimum insulation thickness and cold storage dimensions for a given volume of the cold storage space.

Though the programme is quite general, typical results are displayed for the following data;

1) Volume of the cold storage = $6000 m^3$.

2) Storage conditions = $0^\circ c$ and 35% relative humidity.

3) The upper bounds on the length, breadth and height being 30, 30 and 10 m respectively.

4) Two types of insulating material namely polystyrene foam and thermocole.

The properties and costs of these insulants are

Insulation	Thermal conductivity kJ/(m h $^\circ$c)	Cost per unit volume Rs/m^3
Thermocole	0.17539	1120.00
Polystyrene foam	0.150	2000.00

5) Cost of refrigerating machinery for Ammonia is Rs. 5000/ton.

6) Environmental temperatures and solar radiation data [Appendix-C].

4.2 GRAPHICAL PRESENTATION OF RESULTS

Figure 4.1 shows the variation in ambient temperature and the sol-air temperatures over the different walls and the roof.

Results are presented for conditions prevailing on a typical day in June from 6 AM to 6 PM. " Exact time of sunrise and sunset are not made use of because, solar radiation at sunset and sunrise was not available". From this plot it is seen that sol-air temperature for a horizontal surface (roof) is the highest and is maximum at noon, corresponding to the maximum incident normal solar radiation. From this plot it can be inferred that heat transfer through the west facing and east facing walls is more prominent than that for north and south facing walls. Thus the area of eastern and western walls should be less than that of northern and southern walls.

The variation in design heat load with sink for a typical cold storage having an inside temperature of 0°c, exhibits significant reduction in heat load with sink, Fig. 4.2. The infilt ration heat load also decreases with sink,Fig.4.3. Figure 4.4 shows the percentage reduction in design cooling load with sink. Percentage

reduction in cooling load is given by

$$\% \text{ reduction} = 100 \left[Q_{des,without\ sink} - Q_{des,with\ sink} \right] / \left[Q_{des,without\ sink} \right] \quad .. \quad (4.1)$$

The insulation thickness pertains to that part of the walls which are above the ground level. Insulation thickness for the ceiling is assumed to be 1.5 times that above ground level and thickness for walls below ground level as 0.75 times that above ground level. This plot gives an idea of the saving in cooling load with sink.

Figure 4.5 shows the specimen variation in individual costs with sink. Among all the individual costs, the cost of power is highest. Thus the total cost can be controlled effectively by reduced power cost. This can be achieved by sinking the structure below ground as the cost of power reduces significantly with increase in sink. It is interesting to note that the cost of power at a sink of 9 m is only about 53% of that without any sink for thermocole. This is due to the fact that the cost of power and the cost of refrigerating machinery are dependant on the actual heat load which decreases with increase in sink. The cost of maintenance closely follows the cost of refrigerating machinery.

The only cost that increases with increase in sink is the digging and underground constructional cost.

Low cost of digging and underground construction per unit volume, therefore cannot overcome the effects of the other costs to determine optimum sink. At low unit cost of digging and underground construction minimum total cost occurs at maximum sink. High digging costs, however, result in intermediate values of sink lying between the upper and lower bounds.

Figures 4.6 and 4.7 show the variation in total cost/year with insulation thickness for polystyrene foam insulation and thermocole. These plots are for chosen values of the dimensions which are not optimum values. Variations in different sinks are also shows in these figures. The optimum thickness of insulation can be easily read from these figures corresponding to the minimum total cost/year.

It can be observed from these plots that optimum insulation thickness decreases with increase in sink. Further, the optimum insulation thickness values for polystyrene insulation is considerably less than that for thermocole for the respective sinks. This can be attributed to the fact that the thermal conductivity of the polystyrene foam insulation is less than that for thermocole. The total cost corresponding to the optimum insulation thickness for a particular sink is found to be lesser for thermocole insulation than polystyrene.

Figure 4.8 shows the variation in total cost with insulation thickness for polystyrene insulation. Here the total cost is based on the suggested design approach (consideration of hourly data for temperature radiation). Further the plot is drawn for assumed optimum dimension, i.e. length and breadth. For a given volume and fixed height, it was seen that total cost is minimum for equal values of length and breadth. This can be explained by the fact that for a given volume the cubical shape renders minimum surface area. Minimized surface area results in lesser cost of insulation and lesser heat transfer through ceiling.

Figure 4.9 shows the variation in total cost with insulation thickness for thermocole insulation, based on suggested design approach for optimum dimensions. The saving in total cost for the optimum insulation thickness, for a given sink can be determined by comparing this plot with Fig. 4.7, where the dimensions are not optimized. As an illustration a saving of approximately 1% in total cost was obtained for optimum insulation thickness values for the case of zero sink (when the whole structure is above ground). This saving was seen to decrease with increase in sink.

A saving in total cost can be obtained if thermocole is used instead of polystyrene insulation for

optimized dimensions as can be seen by comparing Fig. 4.3 and Fig. 4.9. As an example a saving of 13 % was obtained for the optimum values corresponding to an intermediate sink of 5 m.

Figure 4.10 depicts the variation in total cost with insulation thickness for polystyrene foam based on standard design conditions (peak value design). It can be ascertained that the suggested design approach is more realistic, by comparing this plot with that of Fig. 4.8 which is based on the suggested design approach. Other parameter remaining the same, a saving of 28% is obtained in cost corresponding to the optimum insulation thickness at a sink of 0 m (whole structure being above ground level). Further the saving in cost increases with increase in sink. It is seen that for a sink of 9 m the saving is 42%.

Similar savings in total cost for thermocole insulation can be ascertained from Fig. 4.11 in comparison with Fig. 4.9. Here a saving of 33% is obtained corresponding to the optimum insulation thickness at a sink of 0 m, based on suggested design approach. A saving of 46% is obtained for a higher sink of 9 m.

Thus it can inferred that the standard design procedure is more severe in the case of thermocole as

compared to polystyrene, as far as saving in total cost is concerned. The variation in total cost with sink for polystyrene foam insulation when the size of the cold storage is fixed can be studied from Fig. 4.12.

It is seen that at low insulation thicknesses the optimum sink lies on or very near the upper bound, for sink which is 9 m. However, the optimum point moves away from the upper bound at higher values of insulation thickness. This can be attributed to the fact that insulation cost overcomes the effect of digging cost on the total cost.

The variation in total cost with sink for thermocole insulation, for the case of the cold storage size being fixed is shown in Fig. 4.13. It can be seen that optimum sink values, at higher insulation thickness, are less for thermocole insulation than that for polystyrene insulation (Figs. 4.13 and 4.12).

The variations in total cost with sink for polystyrene and thermocole insulations, based on the suggested design approach for assumed optimum length and breadth is shown in Figs. 4.14 and 4.15, respectively. The optimum length and breadth has been assumed on the basis that for a given volume the cubical shape renders minimum surface area.

The variations in total cost with sink for polystyrene and thermocole insulations on the basis of standard design conditions is shown in Figs. 4.16 and 4.17, respectively. The total cost corresponding to any insulation thickness for the optimum sink is always higher for polystyrene than thermocole. By comparing Figs. 4.14 and 4.16 it can be seen that a cost saving of 34% can be achieved by the suggested design approach, in the case of polystyrene insulation for an insulation thickness of 8 cm. Similarly, a cost saving of 38% can be achieved for thermocole insulation for the same insulation thickness.

4.3 TABULATED RESULTS

Table 4.1 presents the variation in optimum insulation with inside temperature and sink for thermocole insulation. It is observed that for the same inside temperature the design heat load decreases with increase in sink. But this is not true in the case of total cost variation with sink for all inside temperatures. At some inside temperatures (for cooling) where the cost of power and refrigerating machinery is relatively low, the cost of digging and additional underground constructional cost may overcome the cost of power in increasing the total cost at some sink. In such case the optimum sink lies between the upper and lower bounds of the sink.

This table also gives an idea of the variation in optimum insulation with sink.

Table 4.2 shows the variation in optimum insulation with inside temperature and sink for polystyrene foam insulation.

Results have been tabulated for inside temperatures of 10°c and 4°c (for cooling) and 0°c and - 4°c (for freezing). It is seen that in the case of inside temperature being 10°c the value of the optimum insulation thickness increases after a particular sink indicating an optimum sink between the lower and upper bound of 0 and 9 m., respectively. However in all the other cases the optimum sink lies very near the upper bound. This can be explained by the fact that the cost of power and refrigerating machinery is relatively low for higher inside temperature than for lower inside temperatures. For all the inside temperatures considered the total cost is higher for polystyrene insulation than thermocole. This can be seen by comparing Tables 4.1 and 4.2.

A comparative study of different orientations, insulants and design approaches is presented in Table 4.3. It is seen that orientation has a small effect on design heat load, total cost and the optimum values. The optimum insulation thickness is lesser for the

N-S, E-W orientation, for all the cases, than the NE-SW, NW-SE orientation. This observation helps the designer choose the appropriate orientation.

The suggested design approach is more realistic than the currently practised standard design procedure. In case of thermocole a saving of 35-36% in total cost is achieved for either orientation if the suggested design approach is used. The saving of 30-31% is achieved in case of polystyrene insulation.

It is observed that the optimum sink lies near the lower bound, for both the insulants and orientations considered, when the design approach is based on peak load data, because the cost of digging and additional underground construction is quite low in comparison to the other costs as they do not decrease much with increase in sink so as to affect the total cost.

In case of suggested design approach, for either orientation and insulant, the optimum values for length and breadth are almost equal resulting in minimim surface area. But in case of standard design approach the optimum length and breadth differ because of the greater heat load transmitted through the walls.

Table 4.4 indicates significant reduction in total cost and design heat load for the different insulants

and orientations if the suggested design procedure is used instead of the standard approach.

Presently energy saving is being given wider attention and as such it may be necessary to use higher insulation thickness than the optimum value. In order to study this feasibility the insulation thickness is increased by 20 to 30%, Table 4.5. This renders a saving of 10 to 20% saving in energy, involving only 1-7% increase in total cost, for thermocole insulation. Polystyrene shows higher saving in energy with higher increase in total cost, than thermocole, for suboptimal insulation thickness.

Out of the two suboptimal cases considered 20% higher insulation seems better. If cost is a desired criterion, thermocole is recommended for suboptimal selection. However, polystyrene is preferable when energy conservation is the desired requirement.

CHAPTER - 5

CONCLUSIONS AND SUGGESTIONS

5.1 CONCLUSIONS

From the present study the following conclusions are arrived at:

1. The generalized computer programme for determination of optimum parameters based on hourly load calculation being more realistic as compared to the peak load design has been developed.

2. The heat load and infilt ration load decrease drastically with increase in sink, implying thereby a reduction in functional energy. The cost of power at a sink of 9 m. is only about 58% of that at zero sink. Cost of refrigerating machinery is also reduced by a similar amount with increase in sink.

3. Optimum value of insulation thickness decreases with increase in sink.

4. The optimum insulation thickness of polystyrene insulation is less than that of thermocole for the same sink. But the total cost corresponding to the

optimum insulation thickness for any sink is lesser for thermocole than for polystyrene.

5. The total cost and optimum insulation thickness in the case of optimum dimensions is lesser than that with fixed size, for any insulation.

6. A saving in total cost of 30-36% is achieved by the method outlined in the present work as compared to peak value design approach for either insulant.

7. Change in orientation of the structure does not result in large variations in total cost or optimum values of design parameters.

8. Thermocole insulation is preferred over polystyrene because it results in lesser total cost for the same functional energy. However, if the insulation thickness is to be limited due to practical considerations, polystyrene should be preferred as it results in lesser optimum insulation thickness.

9. In case of the suggested design approach the optimum length and breadth are almost equal. However, they differ by 10-15% in the case of standard design method because of the higher rate of heat transfer through the structure.

10. A study of suboptimal design parameters reveals that a saving of 10 to 20% in functional energy can be achieved with 1-6% increase in total cost when the optimum insulation thickness is increased by 20-30% for thermocole. A similar saving of 15 to 25% in functional energy and increase of 2-15% in total cost is found for polystyrene insulation with 20 to 30% suboptimal insulation thickness. This enables the designer to choose suboptimal insulation thicknesses for the different insulations depending on as to which of the energy and cost requirements is more important for particular applications.

5.2 SCOPE FOR FUTURE WORK

1) A study involving insulants other than those considered in the present work.

2) Application of other optimization techniques to minimize the objective function.

3) Computation of optimum dimensions on the basis of the assumption that the heat transferred through all the walls per unit area is equal.

4) Determination of optimum insulation thickness for each of the four walls.

REFERENCES

1. Chiub, P.C., " Cold Storage Industry-growth, Performance and Promise", All India Seminar on Cold Storages, 16-17 May, 1982, PP. 1-8.

2. Manohar Prasad, "Cold Storage Prospect and Analysis", Dept. of Mech. Engineering, I.I.T., Kanpur.

3. Threlkeld, J.L., "Thermal Environmental Engineering", Prentice Hall, Englewood Cliff, New Jersey, 1970, PP. 312-351.

4. Mackey, C.O., and Wright, L.T., Jr., " Periodic Heat Flow - Composite Walls or Roofs", ASHVE Trans., Vol. 52, 1946, PP. 283-296.

5. Mitals, G.P., " Transfer Function Method of Calculating Loads, Heat Extraction and Space Temperature", ASHRAE Journal, Vol. 14, No. 10, Dec. 1972, PP. 54-56.

6. Kadambi, V., and Hutchinson, F.W., " Refrigeration Air Conditioning and Environmental Control in India", Prentice Hall of India Private Limited, 1968.

7. " ASHRAE Handbook of Fundamentals", 1981, Published by The American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc., New York.

8. McClure, C.J.R., " Optimizing Building Energy Use", ASHRAE Journal, Vol. 13, No. 9, September 1971, PP. 64-72.

9. Bonar, H.B., " Effects of Increased Energy Costs on Refrigeration Warehouse Construction", ASHRAE Journal, Vol. 16, No. 11, November 1974, PP. 53-56.

10. Spielvogel, L.G.," More Insulation can Increase Energy Consumption", ASHRAE Journal, Vol. 16, No. 1, January 1974, PP. 61-63.

11. Gupta, B.D., " Automated Optimum Design of Refrigerated Warehouses and Air Conditioned Buildings", Ph. D. dissertation, Dept. of Mech. Engg., I.I.T., Kanpur, August 1977.

12. Heinze, K., " Refrigerated Warehouse in High Rack Construction, Comparison Cost of Insulation and Exploitation with Those of Single Storey Cold Storages", Progress in Refrigeration on Science and Technology, Vol. III, IIR (Paris), 1973, PP. 417-425.

13. Claesson, A. and Holmqvist, S., " Storage of Cold and Frozen Food in Underground Mined Rock Caverns - An Energy Saving Method of Storage", Refrigeration Science and Technology, 1978, Vol. 2, PP. 319 - 323.

14. Manohar Prasad et. al., " Optimum Insulation Thickness and Depth of Sink for an Underground Cold Storage", Productivity in Cold Storage Industry, Organized by NPC (Chandigarh), Dec. 16-17, 1980.

15. Lokmanhekim, M., and Henninger, R.H., "Computerized Energy Requirement Analysis and Heating Cooling Load Calculation of Building", ASHRAE Journal, Vol. 14, No. 4, April 1972, PP. 25-33.

16. Lokamanhekim, M., " Procedure for determining Heating and Cooling Loads for Computerized Energy Calculations - Algorithms for Building Heat Transfer Sub-routines", ASHRAE, 1971.

17. William Evers, E., " Computerized Energy Analysis", ASHRAE Journal, Vol. 13, No. 9, Sept. 1971, PP. 64-72.

18. Hutchinson, F.W.," Heating Humidifying and Load Analysis", Ronald Press.Co., N.Y., 1962,PP. 232-33.

19. Saluja, S.N. et. al., " Investigation of Soil Temperature Variation", Journal of Institution of Engineers India, Vol. 49, No. 5.

20. Borbely, P., " Borbely, P., " Economic Insulation Thickness", XV International Congress of Refrigeration, Venesia, 23-29 Sept., 1979, D 1-32.

21. Rao, S.S., " Optimization Theory and Applications", Wiley Eastern Limited, 1979.

22. Fox, R.L., " Optimization Methods for Engineering Design", Addison Wesley, Reading, Mass, 1971.

23. Powel, M.J.D., " An Efficient Method for Finding the Minimum of a Function of Several Variables without Calculating Derivatives", Computer Journal, 7(4), 1964, PP. 303-307.

24. Rajaram Prasad, " Optimum Design of Multistage Vapour-Compression Refrigeration System", M.Tech. Thesis, Dept. of Mech. Engg., I.I.T., Kanpur December 1983.

APPENDIX - A

PROPERTIES OF REFRIGERANTS

A.1 AMMONIA R-717:

$$C_p(T) = 2.643 + 0.004643[\ (T-10) + 0.05015\ (T-10)^2]\text{for } T<10$$

$$C_p(T) = 2.14375+0.00396916[(T+45)+0.00006(T+45)^2]\ \text{for } T>10$$

$$h_f(T) = 180.885 + 462.25\ (T/100) + 28.7168\ (T/100)^2 + 13.836\ (T/100)^3 + 5.36214\ (T/100)^4$$

$$h_g(T) = 1443.36 + 111.051\ (T/100) - 85.6543\ (T/100)^2 - 32.7365\ (T/100)^3 + 11.9649\ (T/100)^4$$

$$s_f(T) = 0.712406 + 1.68522\ (T/100) - 0.22175\ (T/100)^2 + 0.0763988\ (T/100)^3 + 0.02347\ (T/100)^4$$

$$s_g(T) = s_f(T) + (h_g(T) - h_f(T))/(T + 273.0)$$

$$r(T) = A + B\ (T/T_{crit}) + c/(T/T_{crit}) + D(T/T_{crit})^2 + E(T/T_{crit})^3 + F[(1-T/T_{crit})^{1.5}/(T/T_{crit})]$$

where $A = 19.66$, $B = -15.5499$, $C = -11.0722$, $D = 9.1141$

$E = -2.152941$, $F = 1.8127$, $T_{crit} = 405.50$

$$p(T) = P_{crit}\ e^r$$

where $P_{crit} = 113.53$

$$\eta_c(r) = 0.9767 - 0.03664\ (r) + 0.001338\ (r)^2$$

APPENDIX - B

B.1 COST OF ELECTRICITY

Year	1972	1976	1977	1978	1979	1981	1983
Cost (Rs/kWh)	0.36	0.43	0.45	0.50	0.55	0.60	0.65

B.2 FORECASTING FUTURE ELECTRICITY COSTS

Let a variable x be defined to represent the number of years from the present. The cost of electricity (c_e) then becomes a function of x. Functional relation between c_e and x has been found in the form:

$$c_e = a/[b + \exp(-cx)] \qquad (B1)$$

If c_{e_i} represents cost of electricity for the year corresponding to $x = x_i$, $i = 1,2,\ldots,n$, the sum of square of errors (when eqn. (B1) is used) is

$$E^2 = \sum_{i=1}^{n} [c_{e_i} - a/ \; b+\exp(-cx_i) \;]^2 \qquad (B2)$$

The constants a,b,c are to be so chosen as to minimize E^2. This has been done using the general minimization technique, considering E^2 as a function of three variables a,b and c.

The following results has been obtained:

a = 1.293
b = 0.97986
c = 0.09338

APPENDIX - C

Refer computer programme and data file

TABLE 4.1

Variation in optimum insulation thickness with inside temperature and sink.

THERMOCOLE INSULATION SUGGESTED DESIGN APPROACH

Inside Temp. $0^\circ c$	Sink (m)	Q_{des} kJ/hr	Total cost Rs./year	Optimum insulation (m)		
				t	t_R	t_1
10.0	0	109163.62	31147.23	0.0846	0.1472	0.0626
	3	95396.20	30289.91	0.0784	0.13563	0.0572
	6	84738.99	30124.34	0.0693	0.1202	0.0503
	9	75050.67	30233.10	0.0699	0.12093	0.0510
4.0	0	119831.83	35125.94	0.0978	0.1712	0.0734
	3	103846.93	33801.41	0.0891	0.1550	0.06593
	6	91788.02	33358.41	0.0792	0.13702	0.05782
	9	81144.82	33298.25	0.0683	0.11747	0.0505
0.0	0	124773.75	37772.16	0.1121	0.19393	0.08183
	3	107276.88	36110.78	0.10163	0.17632	0.07469
	6	94307.62	35468.04	0.0898	0.154905	0.06510
	9	83142.48	35297.89	0.0803	0.13812	0.05782
-4.0	0	129459.11	40332.66	0.1203	0.2105	0.0902
	3	110511.77	38340.95	0.1159	0.20167	0.0858
	6	96709.65	37507.44	0.1081	0.18701	0.7892
	9	85121.53	37238.67	0.0937	0.16163	0.0679

TABLE 4.2

Variation in optimum insulation thickness with inside temperature and sinks

POLYSTYRENE FOAM INSULATION SUGGESTED DESIGN APPROACH

Inside Temp. °c	Sink (m)	Q_{des} kJ/hr	Total cost Rs./Year	Optimum insulation (m) t	t_R	t_1
10	0	126965.52	36463.16	0.0644	0.1127	0.0483
	3	115874.09	34982.19	0.0561	0.0976	0.0415
	6	94915.97	34213.04	0.0509	0.0881	0.0372
	9	86988.19	33570.46	0.0453	0.0781	0.0328
4	0	149402.00	44232.20	0.0719	0.1258	0.0539
	3	134263.72	41944.85	0.0593	0.1032	0.0439
	6	110620.19	40839.57	0.0591	0.1022	0.0431
	9	100540.6	39540.67	0.0508	0.0881	0.0371
0	0	130578.4	40619.98	0.0751	0.1314	0.05632
	3	115592.19	40875.50	0.0693	0.1205	0.0513
	6	111630.31	40833.00	0.0650	0.1125	0.0475
	9	105536.36	40844.73	0.0583	0.1009	0.0426
-4	0	135578.83	40185.79	0.1033	0.1808	0.0775
	3	109782.22	38204.79	0.1061	0.1846	0.0785
	6	96064.03	37386.61	0.1009	0.1735	0.0726
	9	84574.02	37136.15	0.0968	0.1675	0.0707

TABLE 4.3

OPTIMUM PARAMETER VALUES FOR DIFFERENT INSULANTS, ORIENTATIONS AND DESIGN APPROACHES (INSIDE TEMP = 0°c)

INSULATION	DESIGN APPROACH	ORIENTATION	OPTIMUM PARAMETERS							Total cost Rs/year	$\dot{Q}_{des}$ kJ/hour
			t(m)	t_R(m)	t_1(m)	s(m)	a(m)	b(m)	H(m)		
Thermocole	Suggested	N-S, E-W	0.08950	0.1583	0.0671	7.998	20.90	19.97	14.38	33881.11	88737.96
Thermocole	Standard	N-S, E-W	0.1494	0.1999	0.1120	0.001	23.49	18.08	14.12	52545.61	136622.12
Thermocole	Suggested	NE-SW, NW-SE	0.0903	0.1598	0.0677	8.036	21.12	19.89	14.28	33912.27	89126.03
Thermocole	Standard	NE-SW, NW-SE	0.1524	0.2039	0.1143	0.003	24.45	18.00	13.63	53010.14	137009.46
Polystyrene	Suggested	N-S, E-W	0.0709	0.0969	0.0530	8.432	21.06	20.12	14.16	42673.69	94010.34
Polytyrene	Standard	N-S, E-W	0.1199	0.1639	0.0899	0.002	22.73	18.06	14.62	61529.22	138615.92
Polystyrene	Suggested	NE-SW, NW-SE	0.0734	0.1003	0.0592	8.619	22.10	21.20	12.81	43121.10	94920.12
Polystyrene	Standard	NE-SW, NW-SE	0.1213	0.1690	0.0913	0.003	23.69	18.13	13.98	62223.10	139507.33

Upper bound on insulation = 0.20 m.

Upper bound on length and breadth = 30 m.

TABLE 4.4

Percentage reduction in total cost and design heat load over standard design approach.

Insulation	Orientation	% cost Reduction	% reduction in design heat load
Thermocole	N-S, E-W	35.52	34.96
Thermocole	NE-SW, NW-SE	36.02	34.38
Polystyrene	N-S, E-W	30.64	32.17
Polystyrene	NE-SW, NW-SE	30.69	31.96

TABLE 4.5

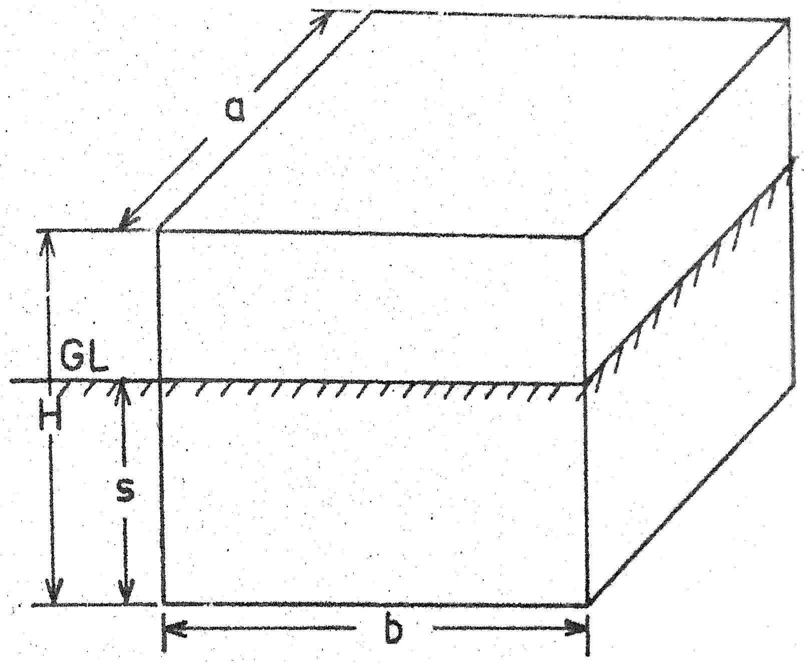
Optimum insulation thickness values, energy saving and cost increase for 20% and 30% suboptimal values

THERMOCOLE

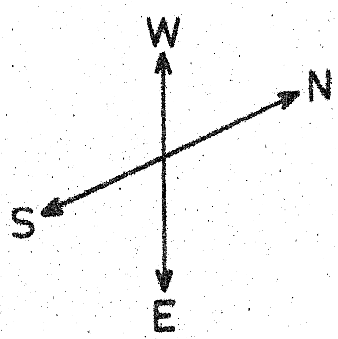
INSIDE TEMP. °c	t_{opt} (m)	$t_{R\ opt}$ (m)	$t_{1\ opt}$ (m)	20% increase: % $\dot{Q}_{des}$ decrease	20% increase: % cost increase	30% increase: % $\dot{Q}_{des}$ decrease	30% increase: % cost increase
10.0	0.07036	0.11063	0.0531	9.0	0.59	15.56	1.73
4.0	0.07811	0.13956	0.0551	11.05	0.786	17.137	2.14
0.0	0.08950	0.1583	0.0671	13.12	1.017	18.33	3.16
-4.0	0.1236	0.18373	0.0716	15.37	2.36	20.89	6.73

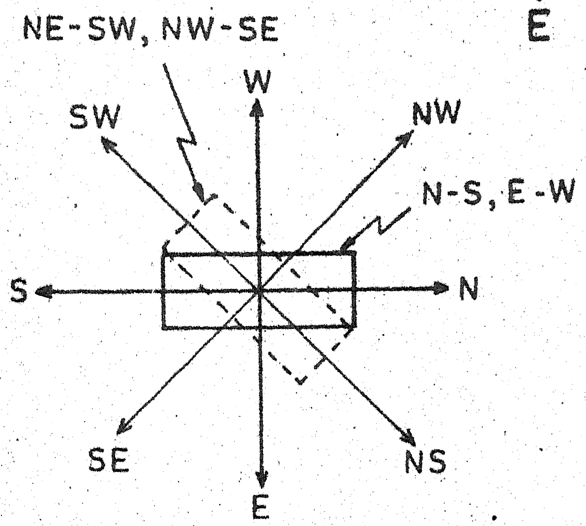
POLYSTYRENE

INSIDE TEMP. °c	t_{opt} (m)	$t_{R\ opt}$ (m)	$t_{1\ opt}$ (m)	20% increase: % $\dot{Q}_{des}$ decrease	20% increase: % cost increase	30% increase: % $\dot{Q}_{des}$ decrease	30% increase: % cost increase
10.0	0.0523	0.0715	0.04-	12.13	1.35	13.4	2.08
4.0	0.0611	0.0872	0.0472	14.2193	1.65	18.248	4.86
0.0	0.0709	0.09692	0.0530	18.072	1.99	21.332	9.11
-4.0	0.0983	0.1332	0.0712	22.99	2.63	24.963	13.89



GL - GROUND LEVEL





ORIENTATION

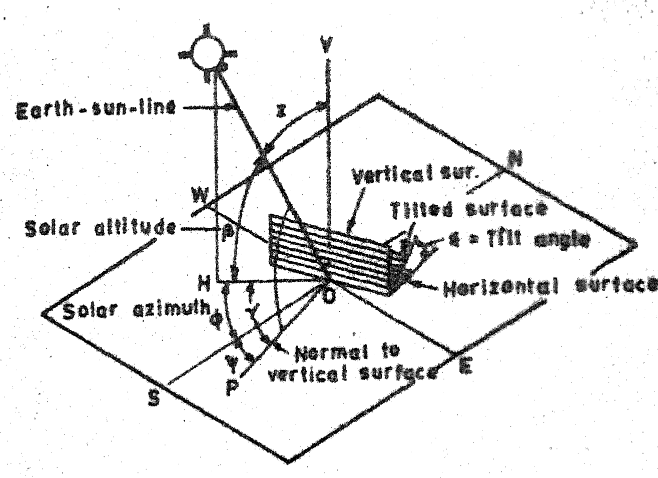


FIG. 2.4

FIG. 2.1 SHAPE AND ORIENTATION OF THE COLD STORAGE.

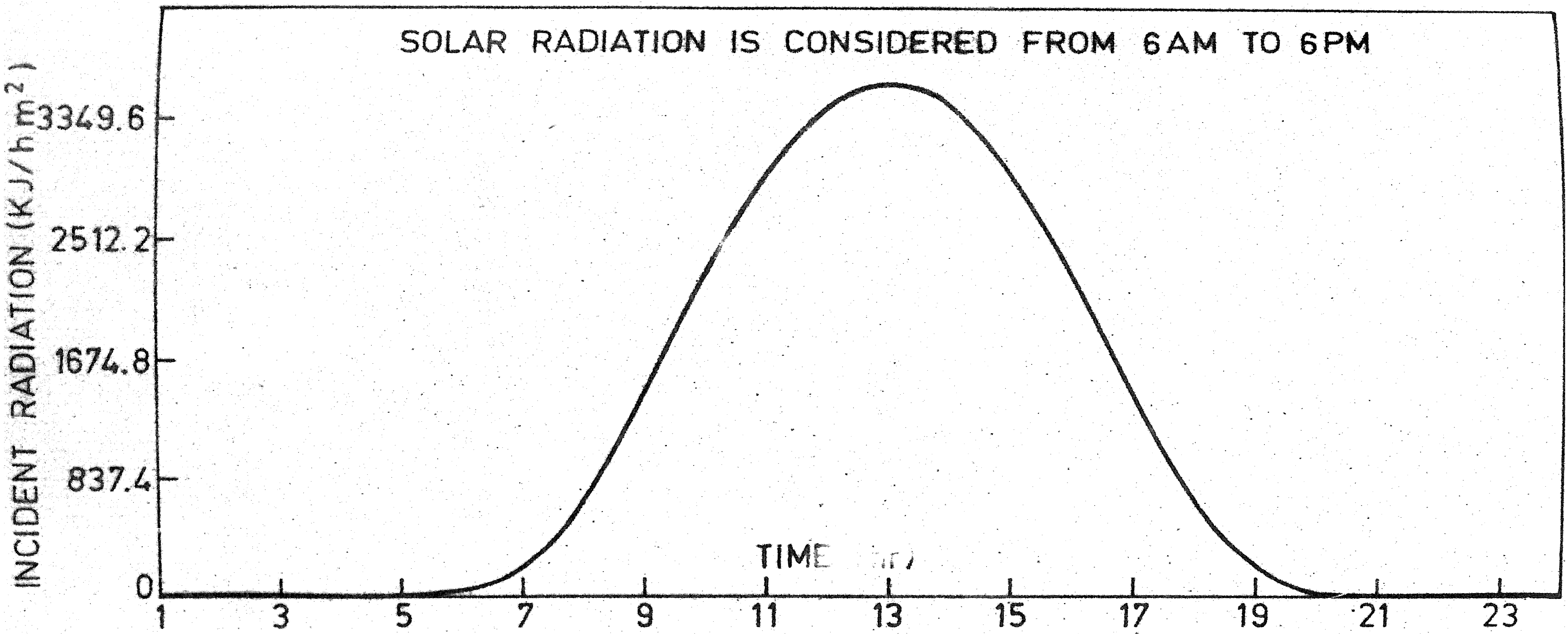


FIG. 2.3 VARIATION OF INCIDENT RADIATION WITH TIME

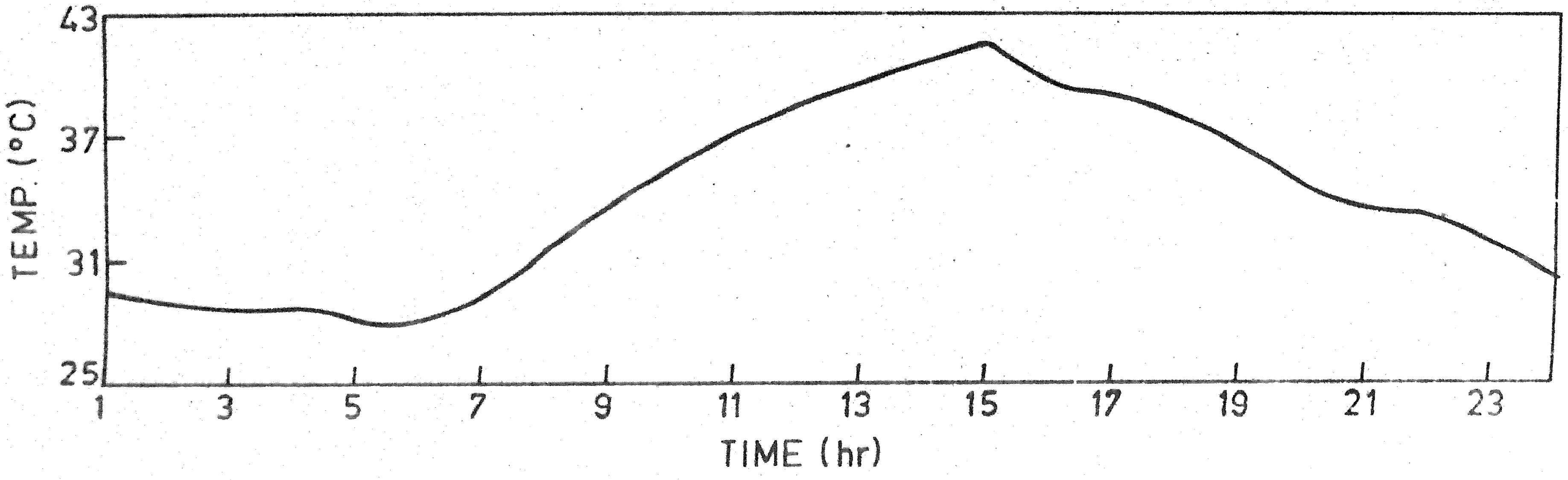
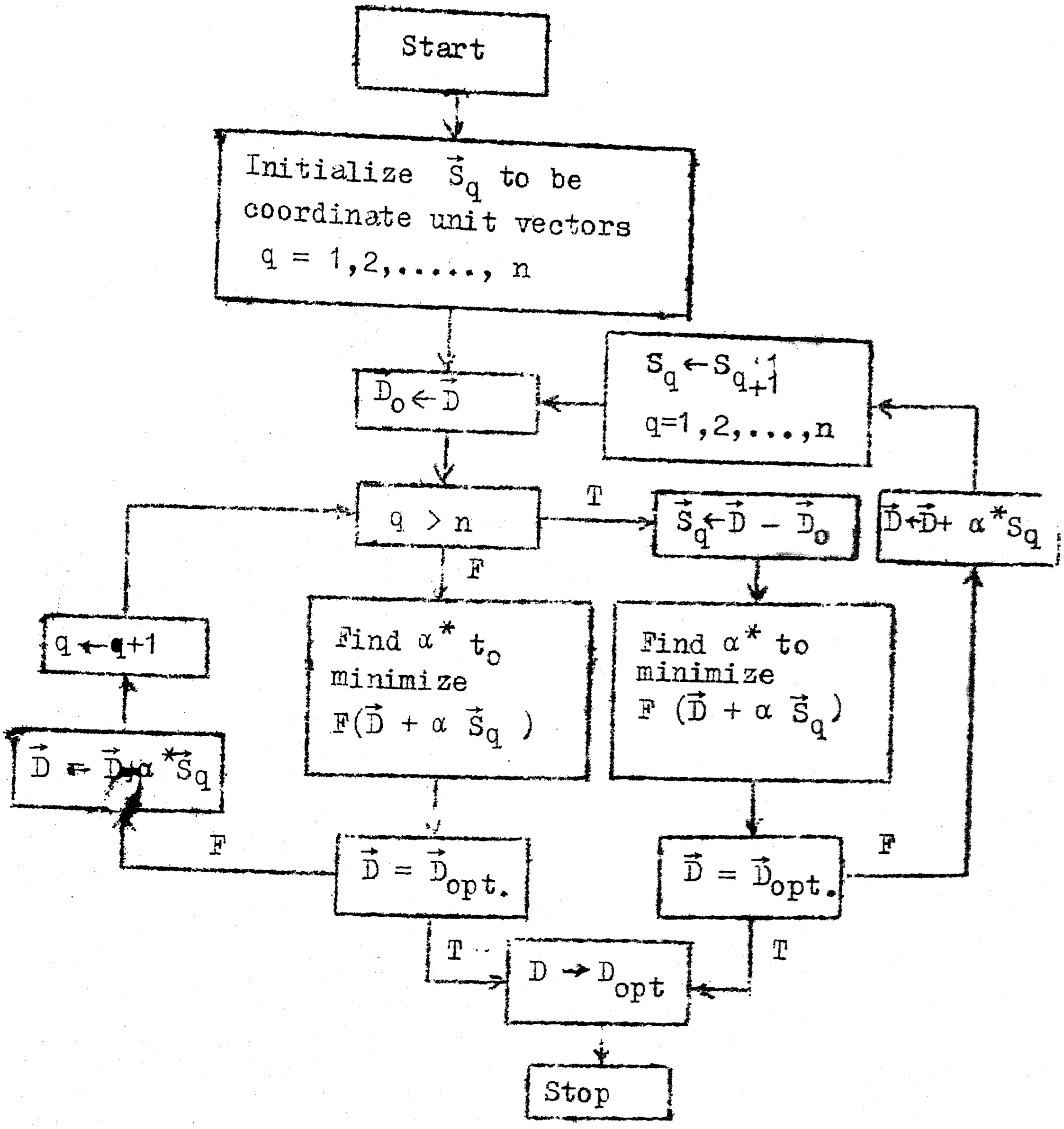


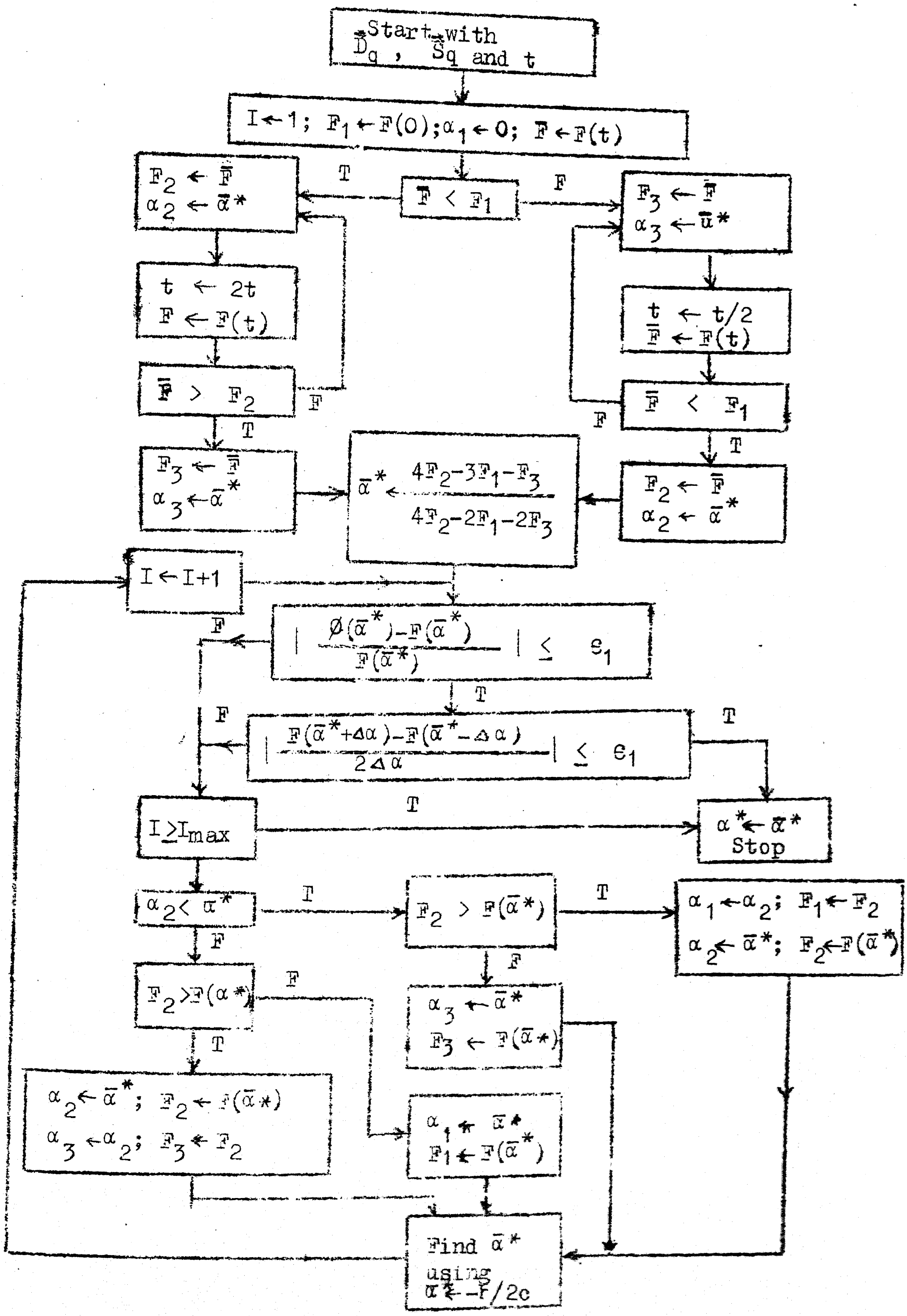
FIG. 2.2 VARIATION OF AMBIENT TEMPERAT WITH TIME



F : False

T : True

FIG. 3.1 : FLOW DIAGRAM FOR POWELL ALGORITHM



T : True
F : False

FIG. 3.2 : FLOW DIAGRAM FOR QUADRATIC FIT

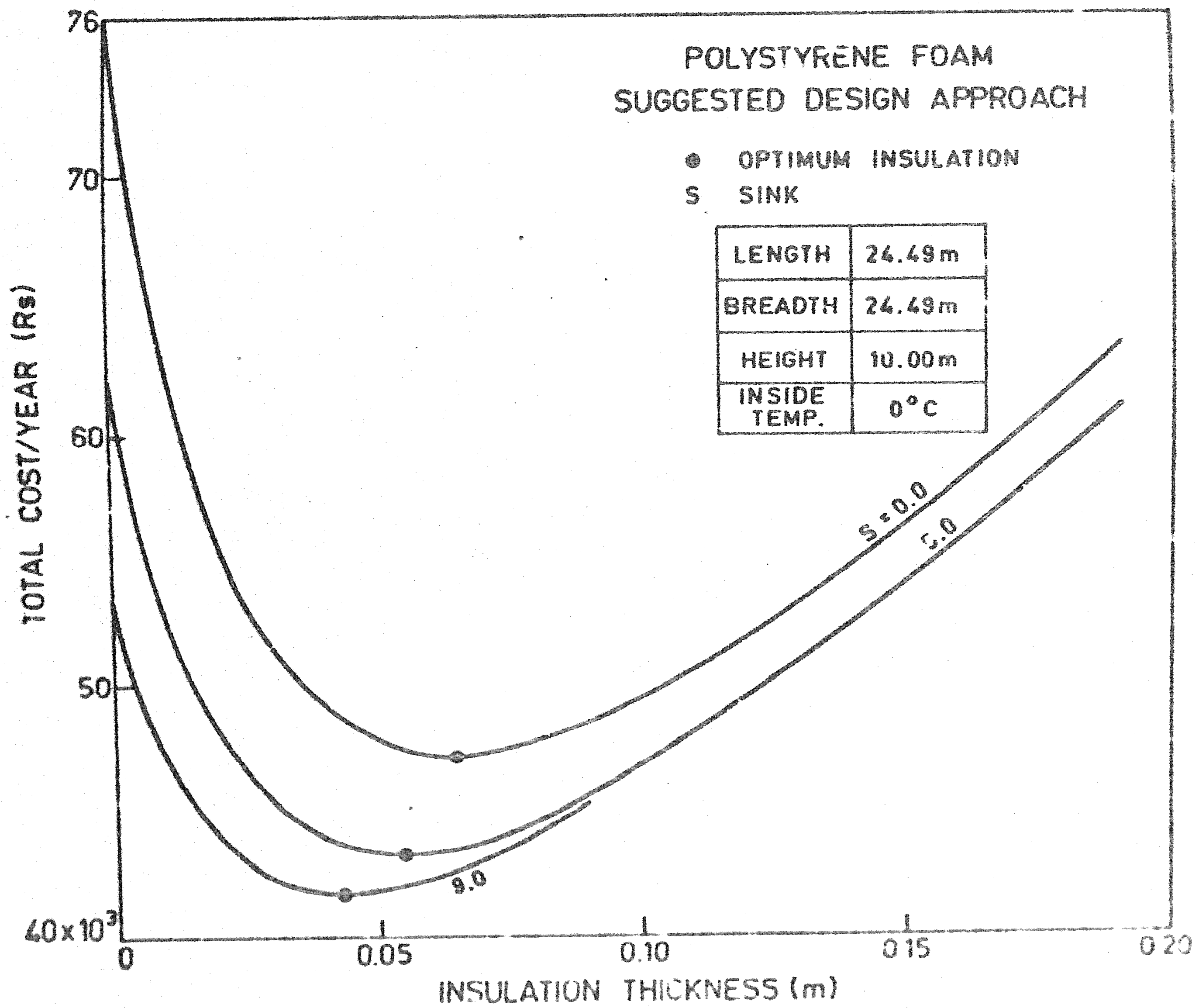


FIG 4.8 VARIATION IN TOTAL COST WITH INSULATION THICKNESS

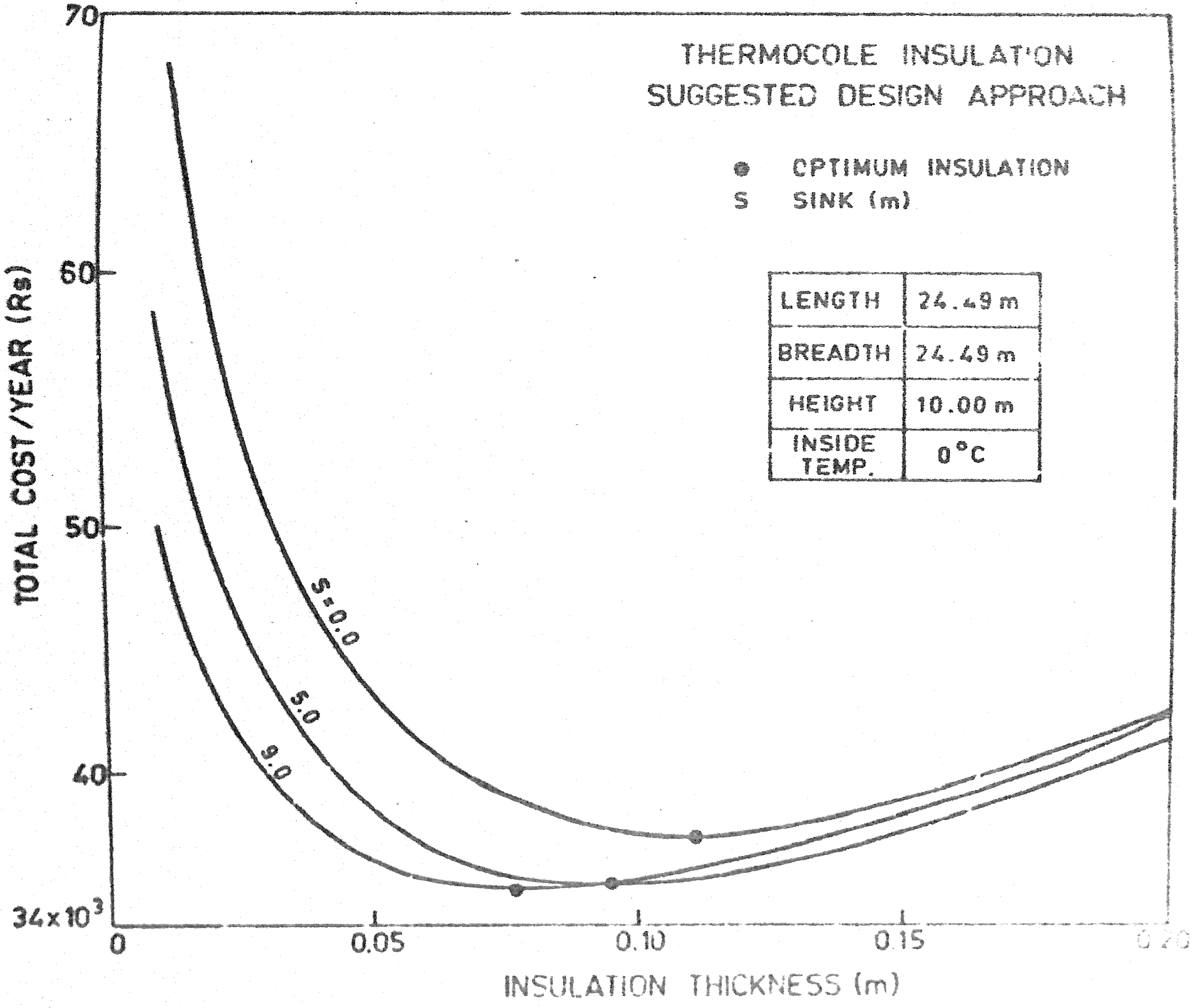


FIG. 4.9 VARIATION IN TOTAL COST WITH INSULATION THICKNESS

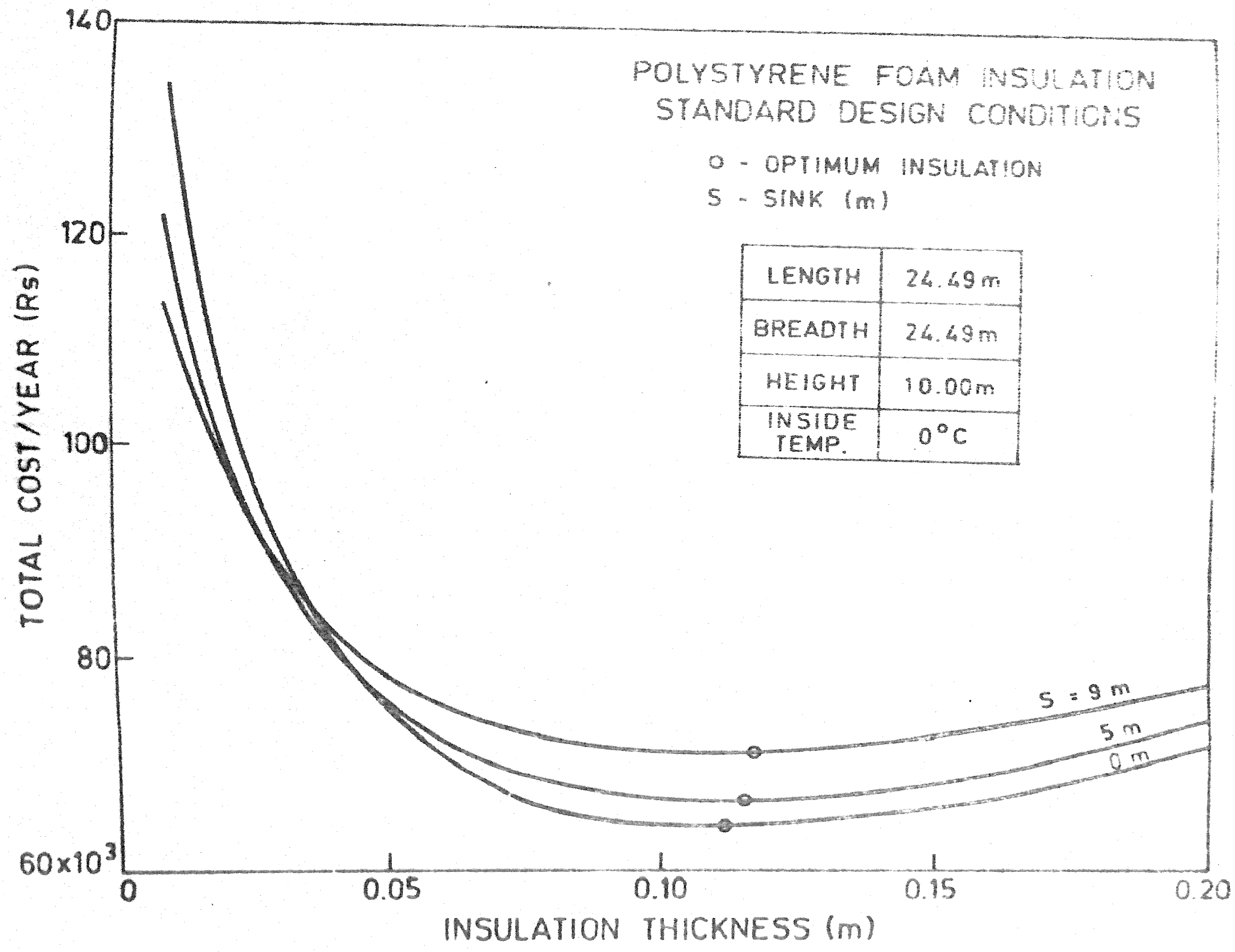


FIG. 4.10 VARIATION IN TOTAL COST WITH INSULATION THICKNESS

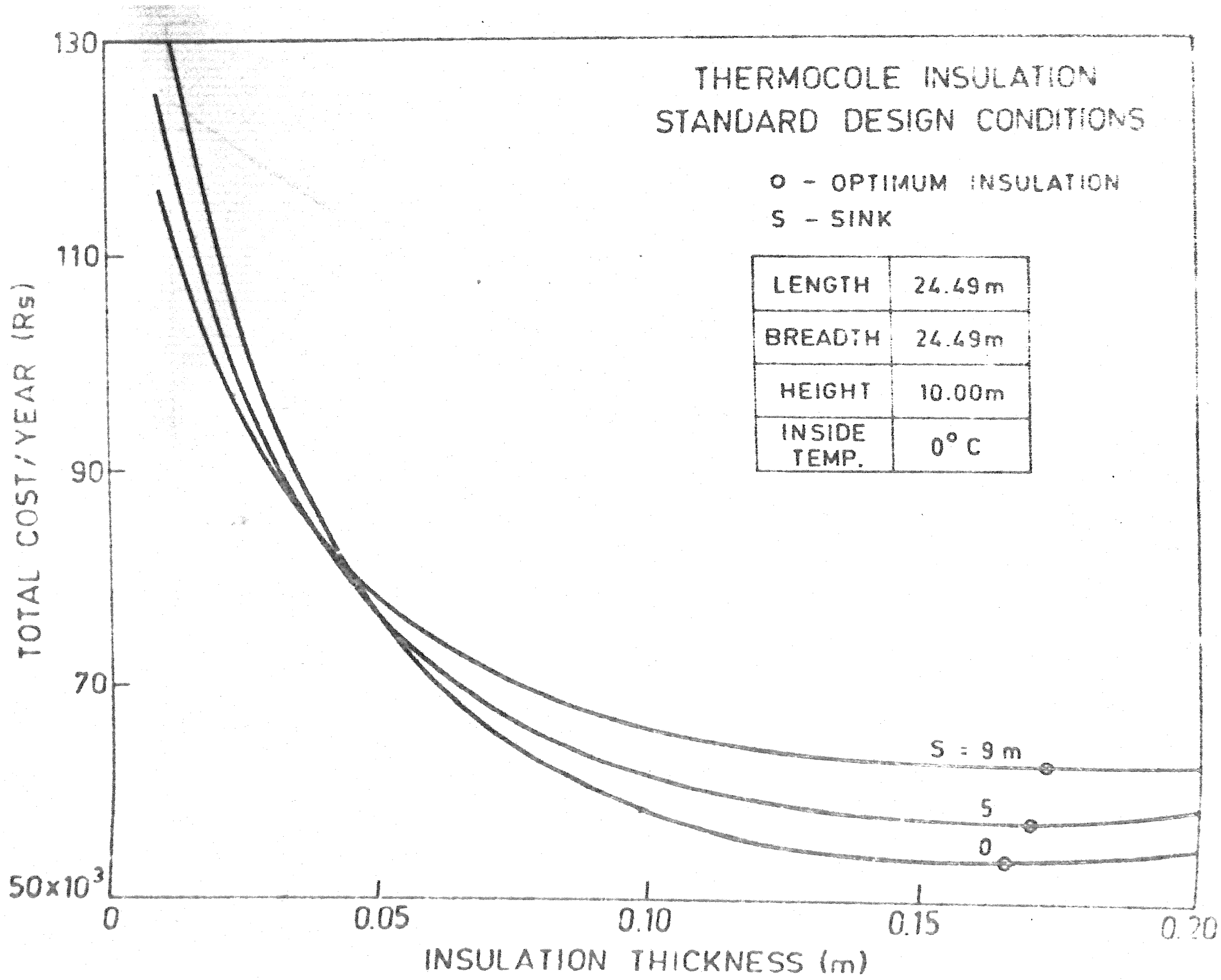
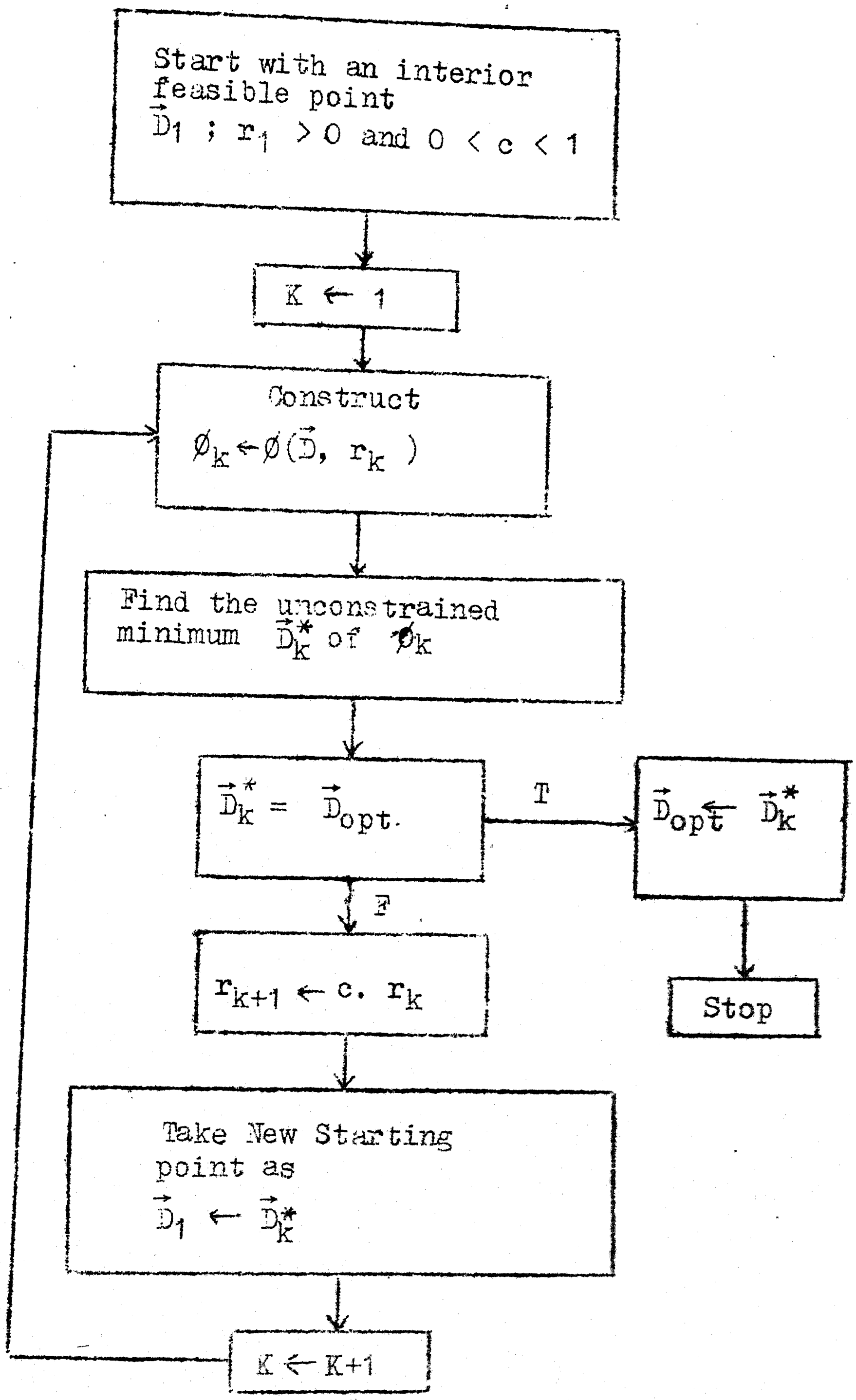


FIG. 4.11 VARIATION IN TOTAL COST WITH INSULATION THICKNESS



T : True
F : False

FIG. 3.3 : FLOW DIAGRAM FOR INTERIOR PENALTY FUNCTION METHOD

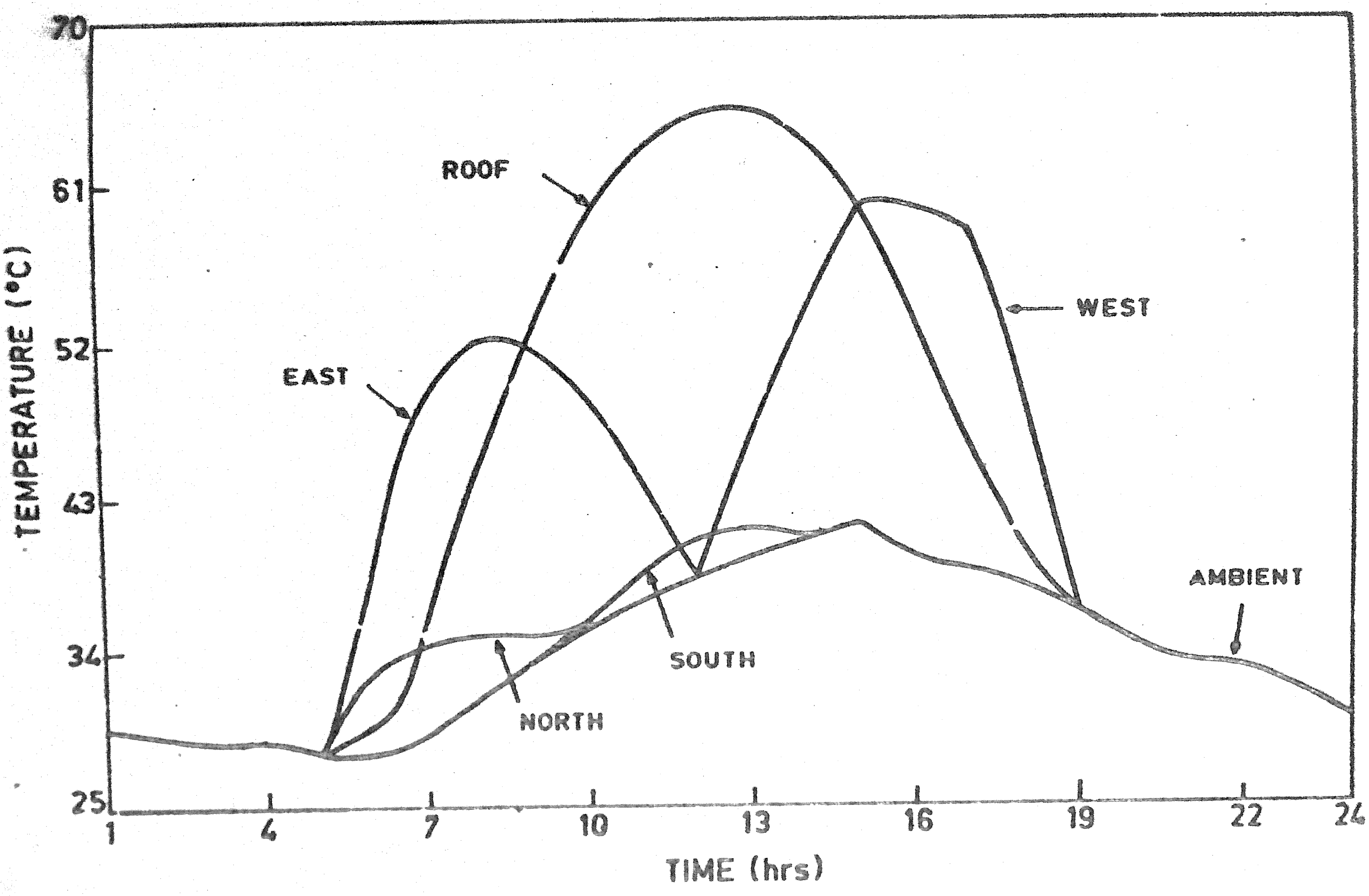


FIG. 4.1 VARIATION IN AMBIENT AND SOL-AIR TEMPERATURE WITH TIME

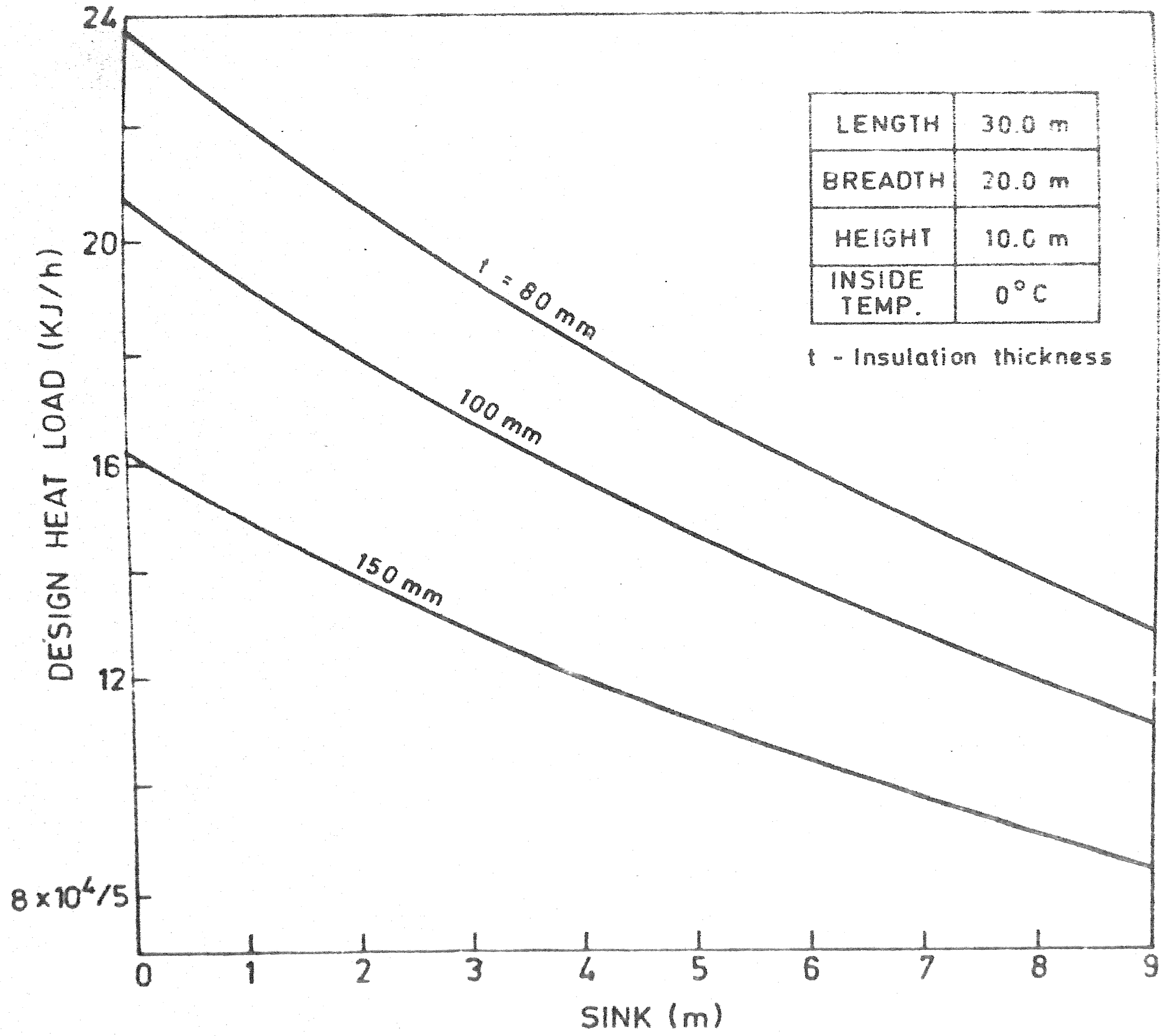


FIG. 4.2 VARIATION IN DESIGN HEAT LOAD WITH SINK

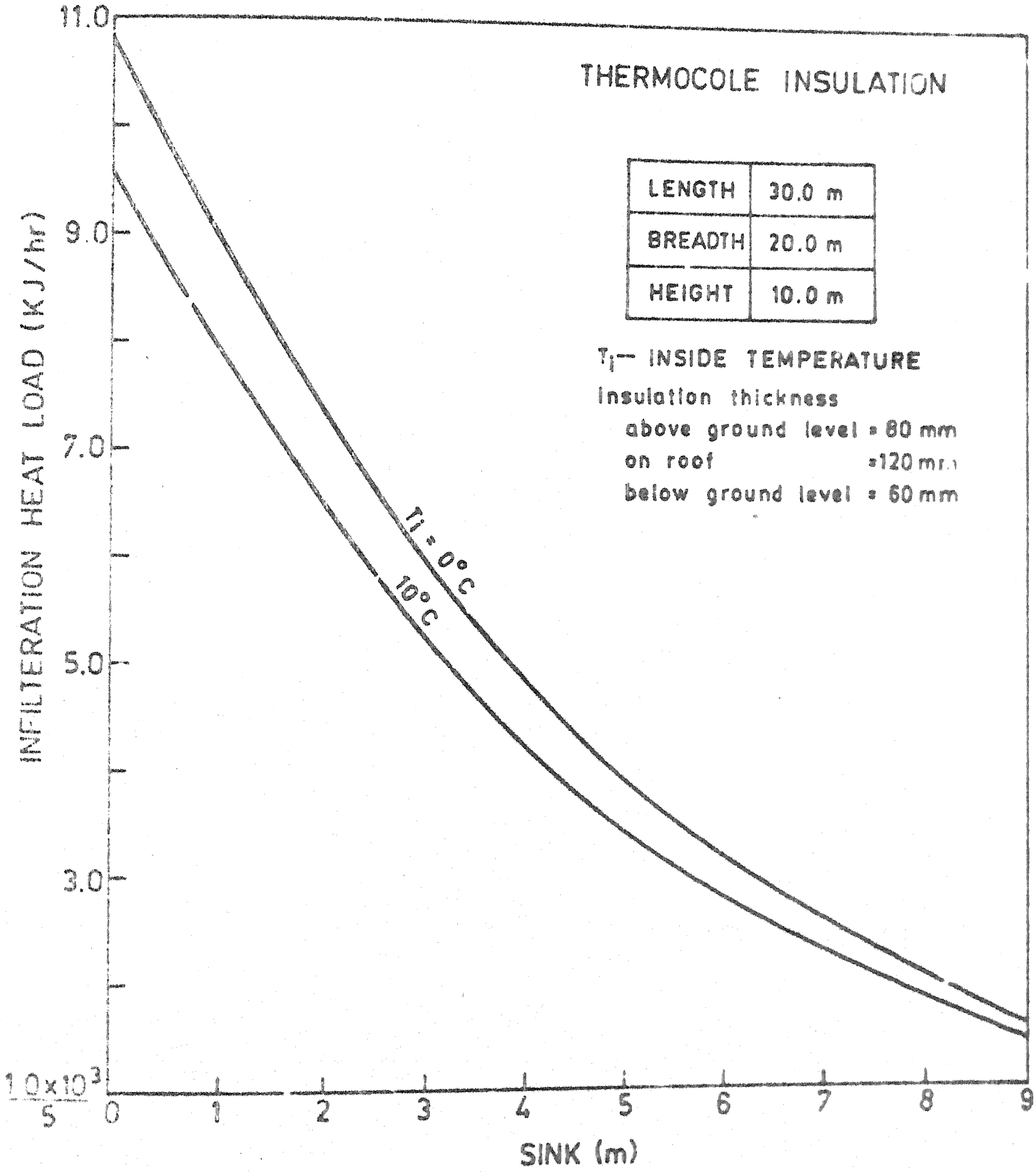


FIG. 4.3 VARIATION IN INFILTERATION HEAT LOAD WITH SINK

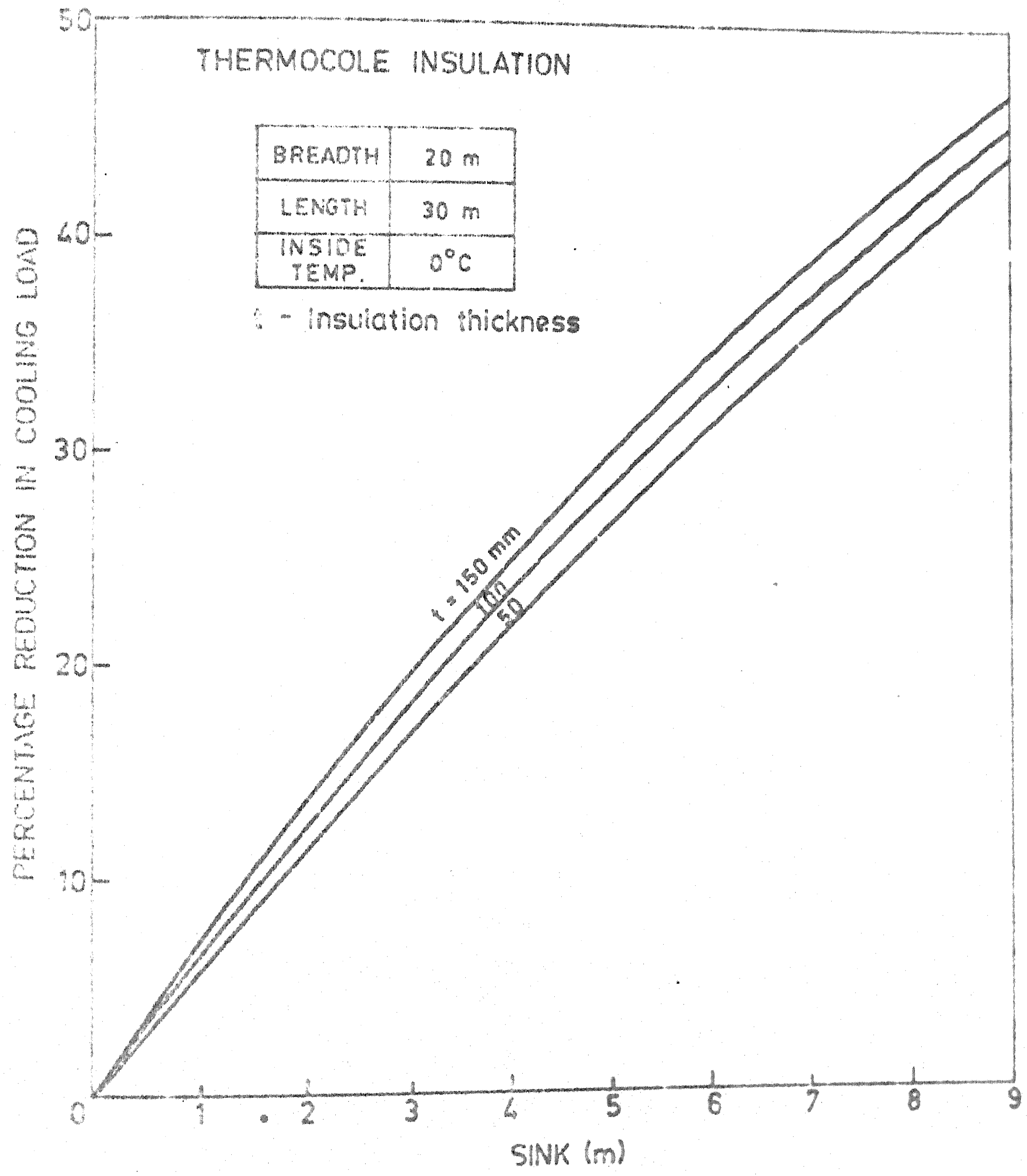


FIG. 4.4 PERCENTAGE REDUCTION IN COOLING LOAD WITH SINK

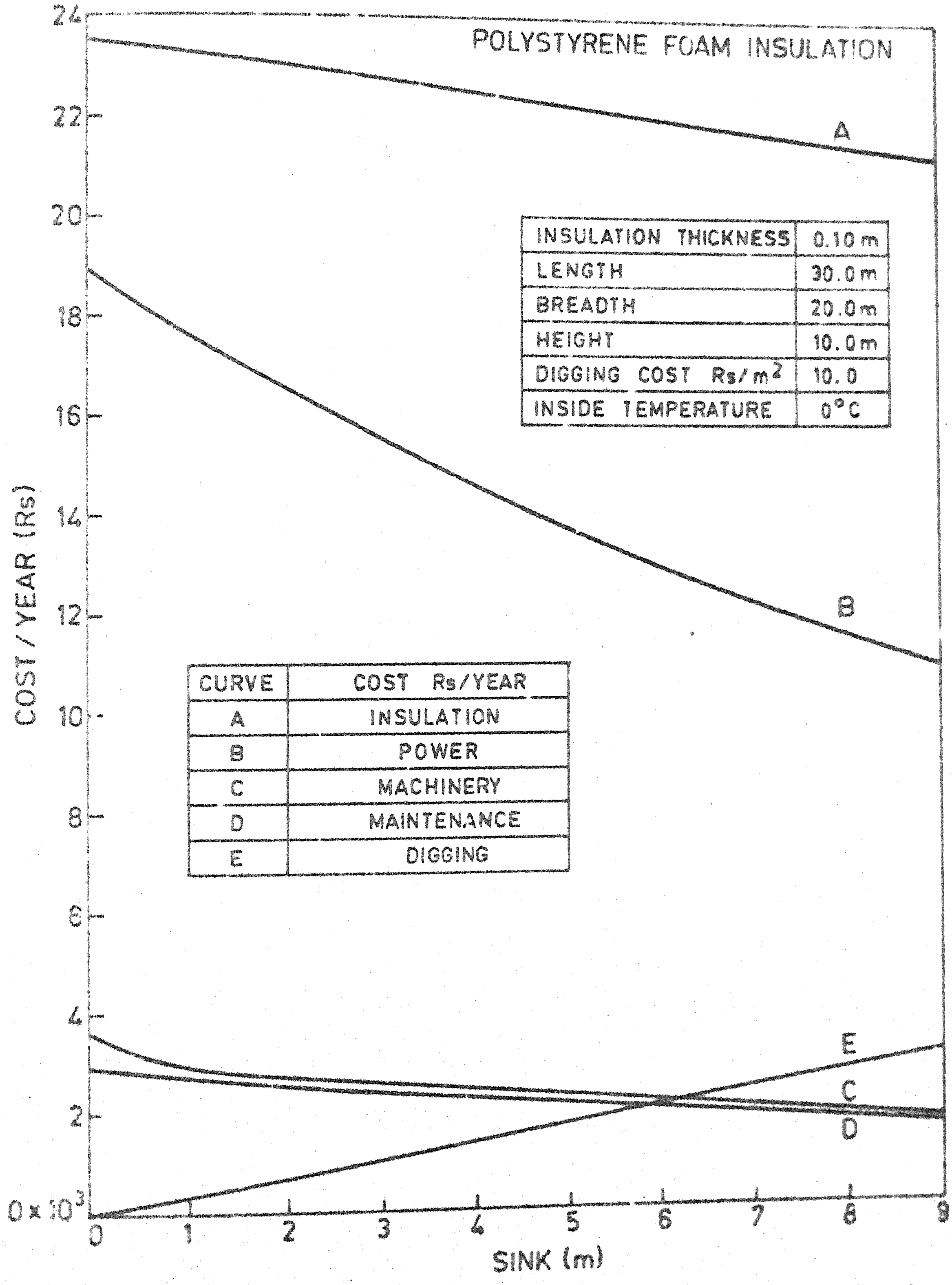


FIG. 4.5 SPECIMEN VARIATION IN INDIVIDUAL COSTS WITH SINK.

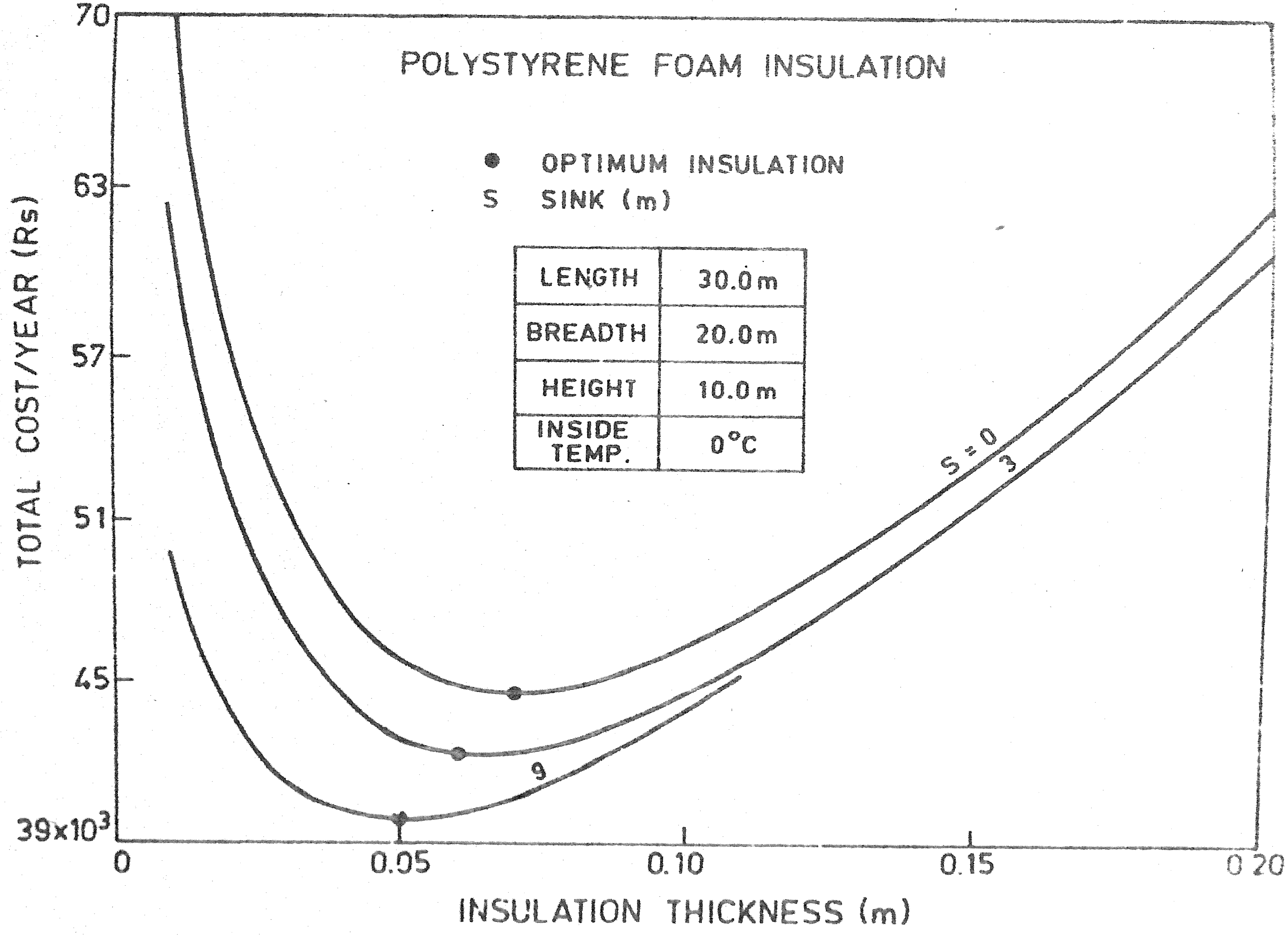


FIG. 4.6 VARIATION IN TOTAL COST WITH INSULATION THICKNESS

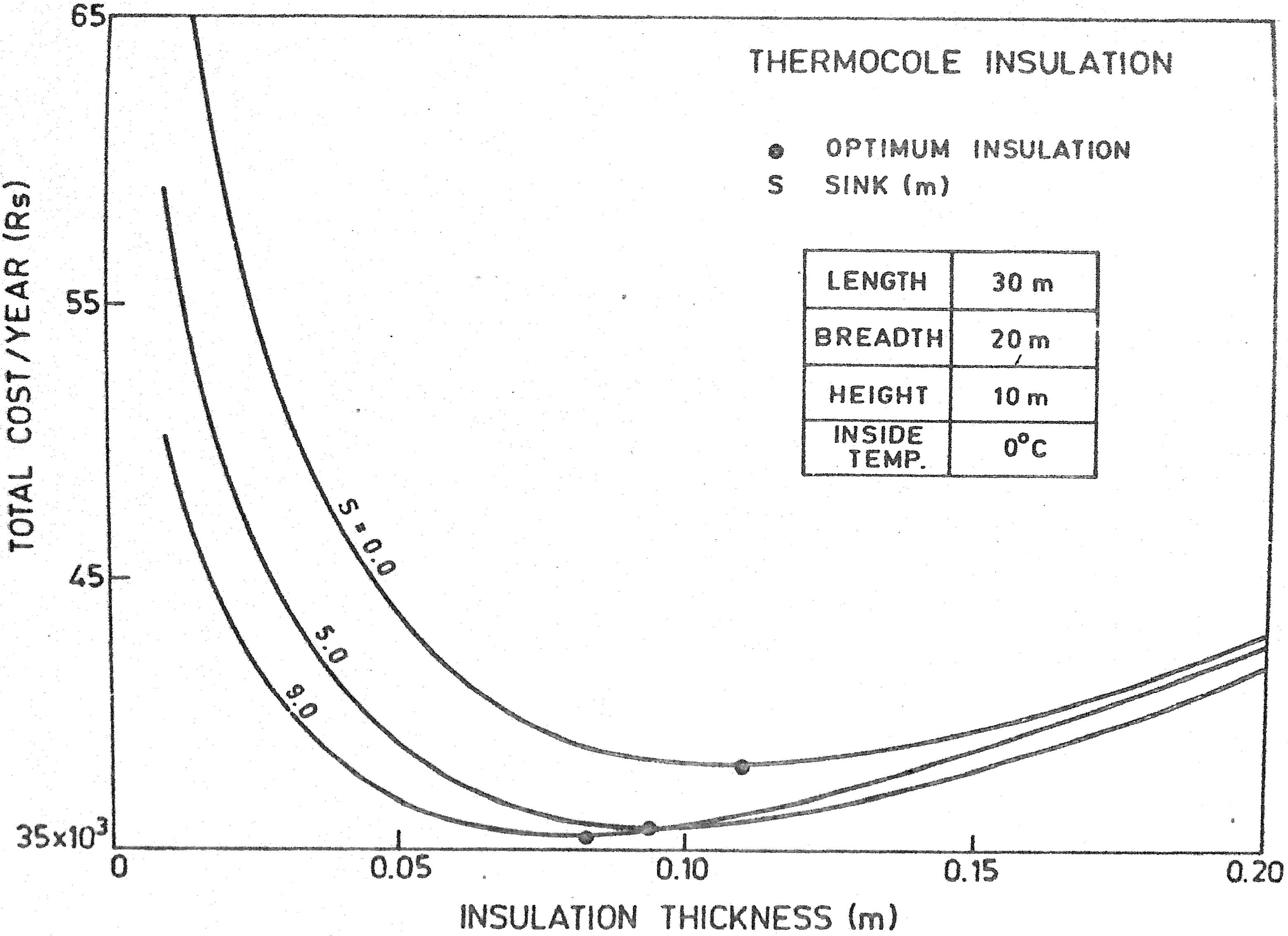


FIG. 4.7 VARIATION OF TOTAL COST WITH INSULATION THICKNESS.

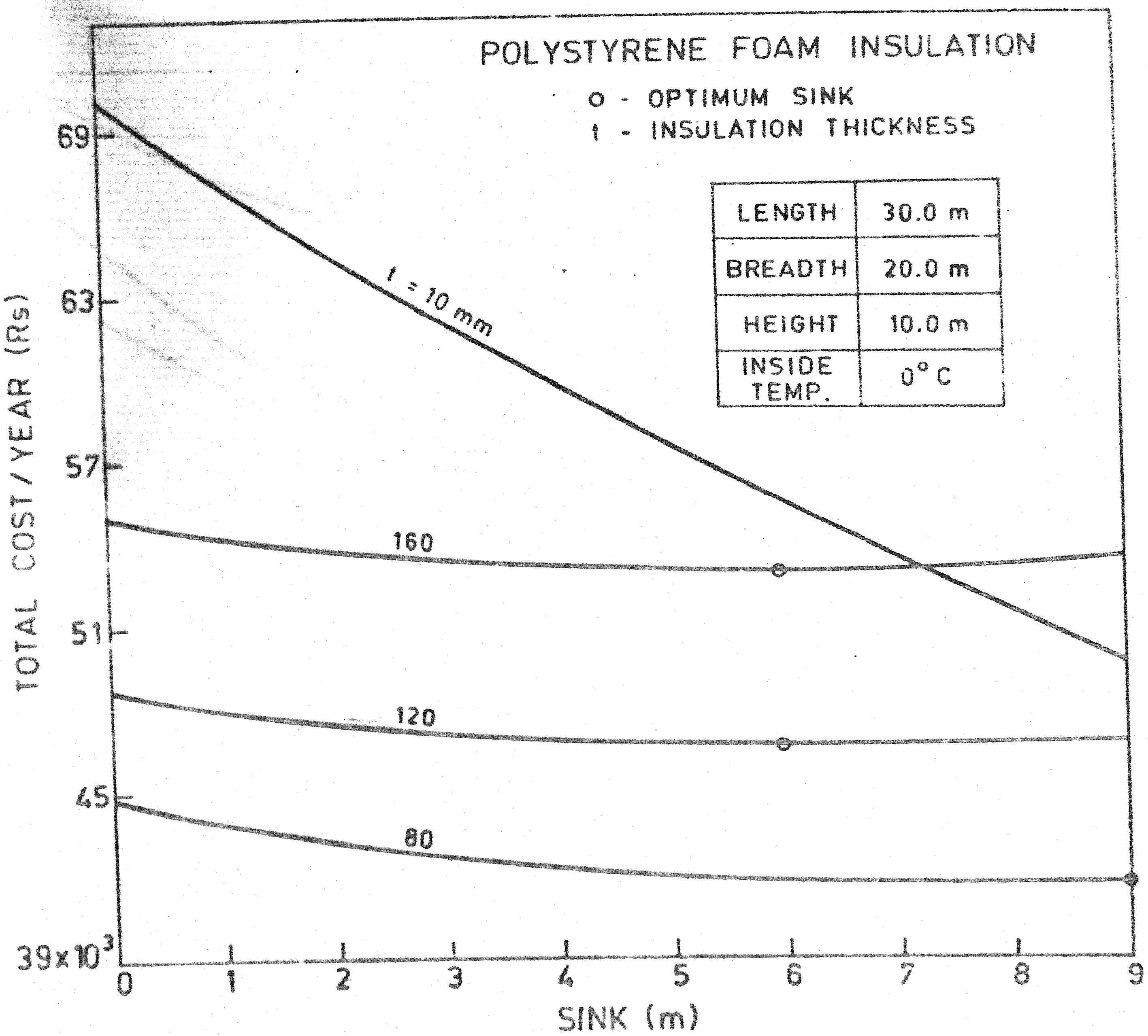


FIG. 4.12 VARIATION IN TOTAL COST WITH SINK.

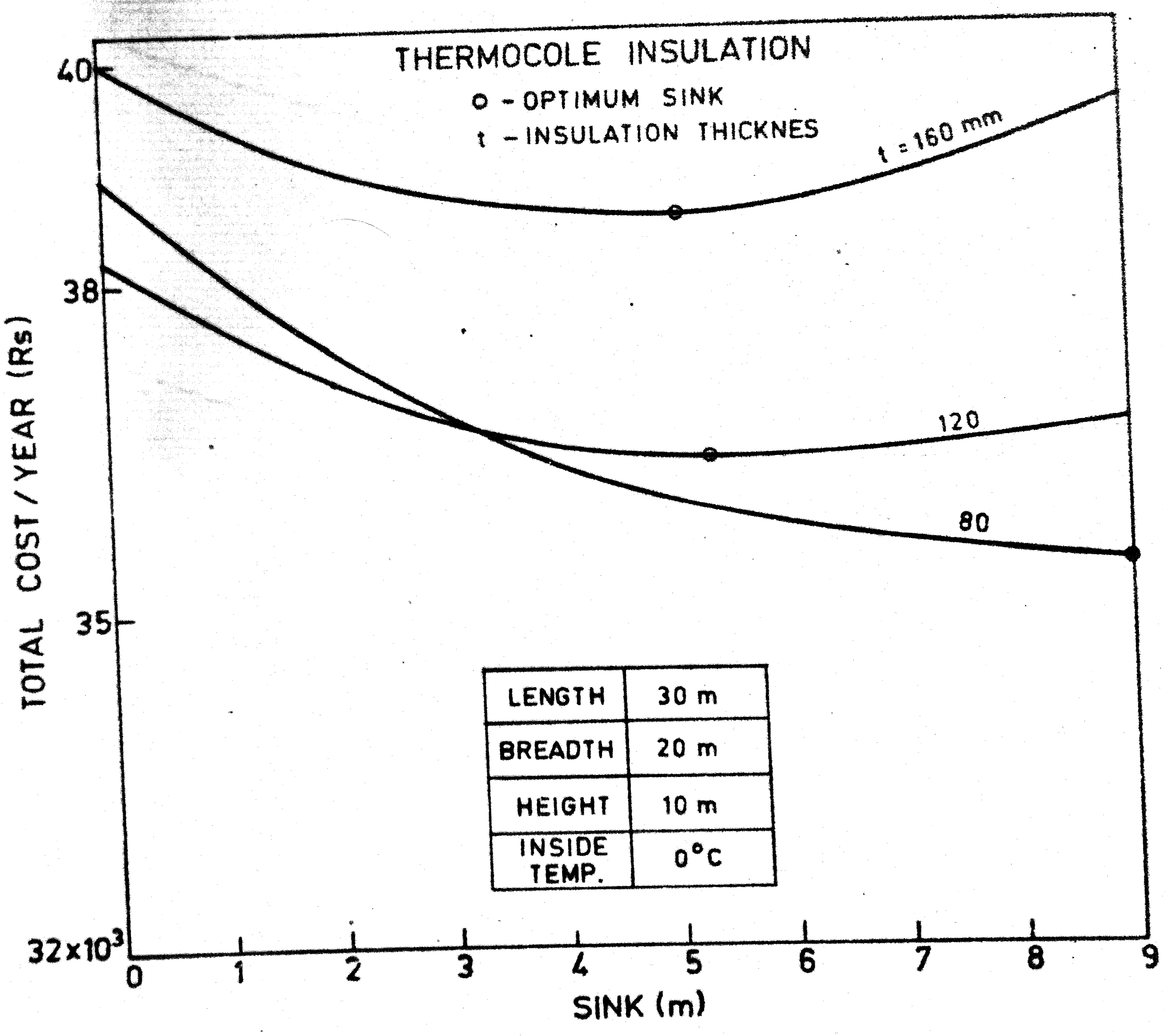


FIG. 4.13 VARIATION IN TOTAL COST WITH SINK.

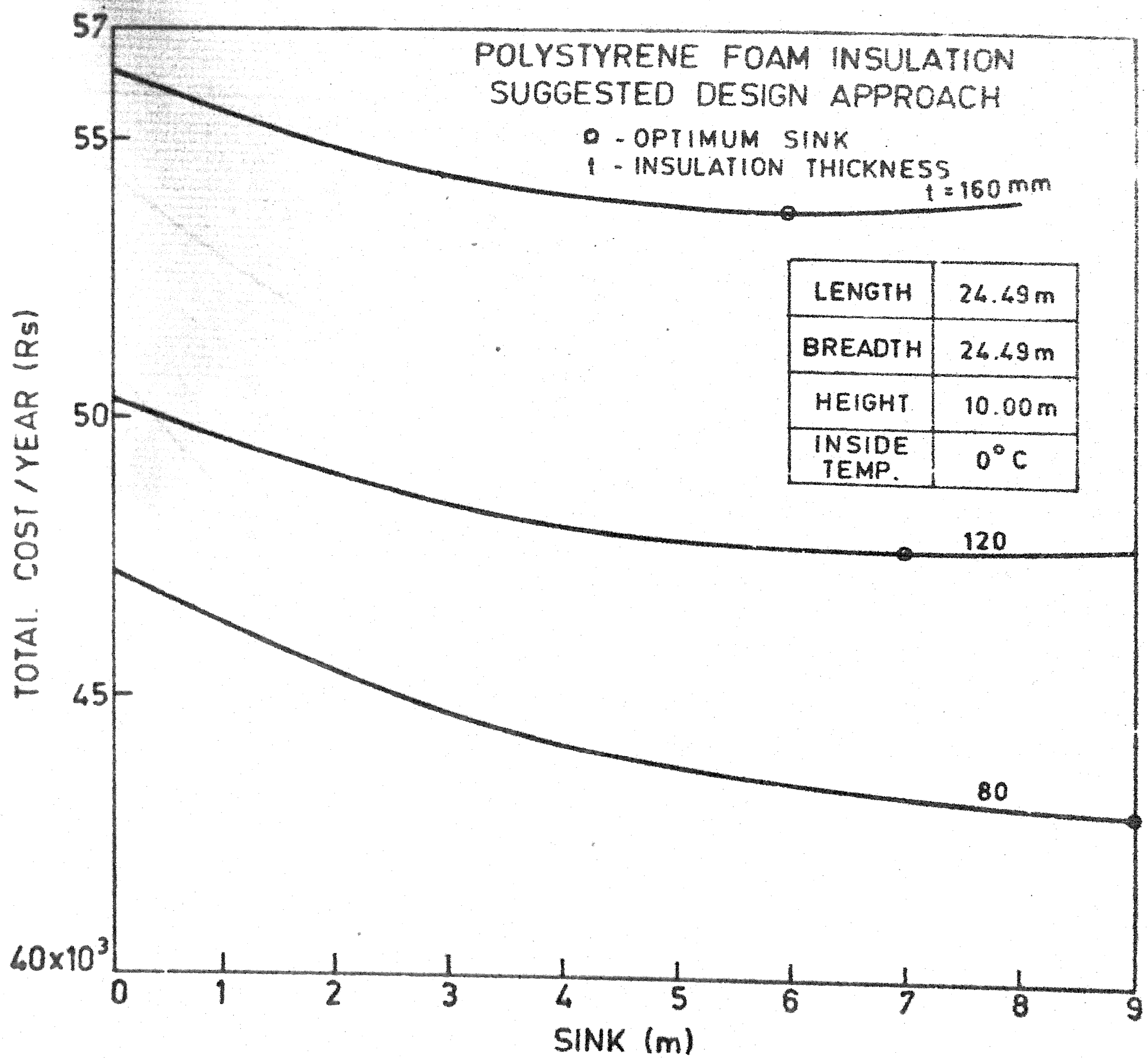


FIG. 4.14 VARIATION OF TOTAL COST WITH SINK.

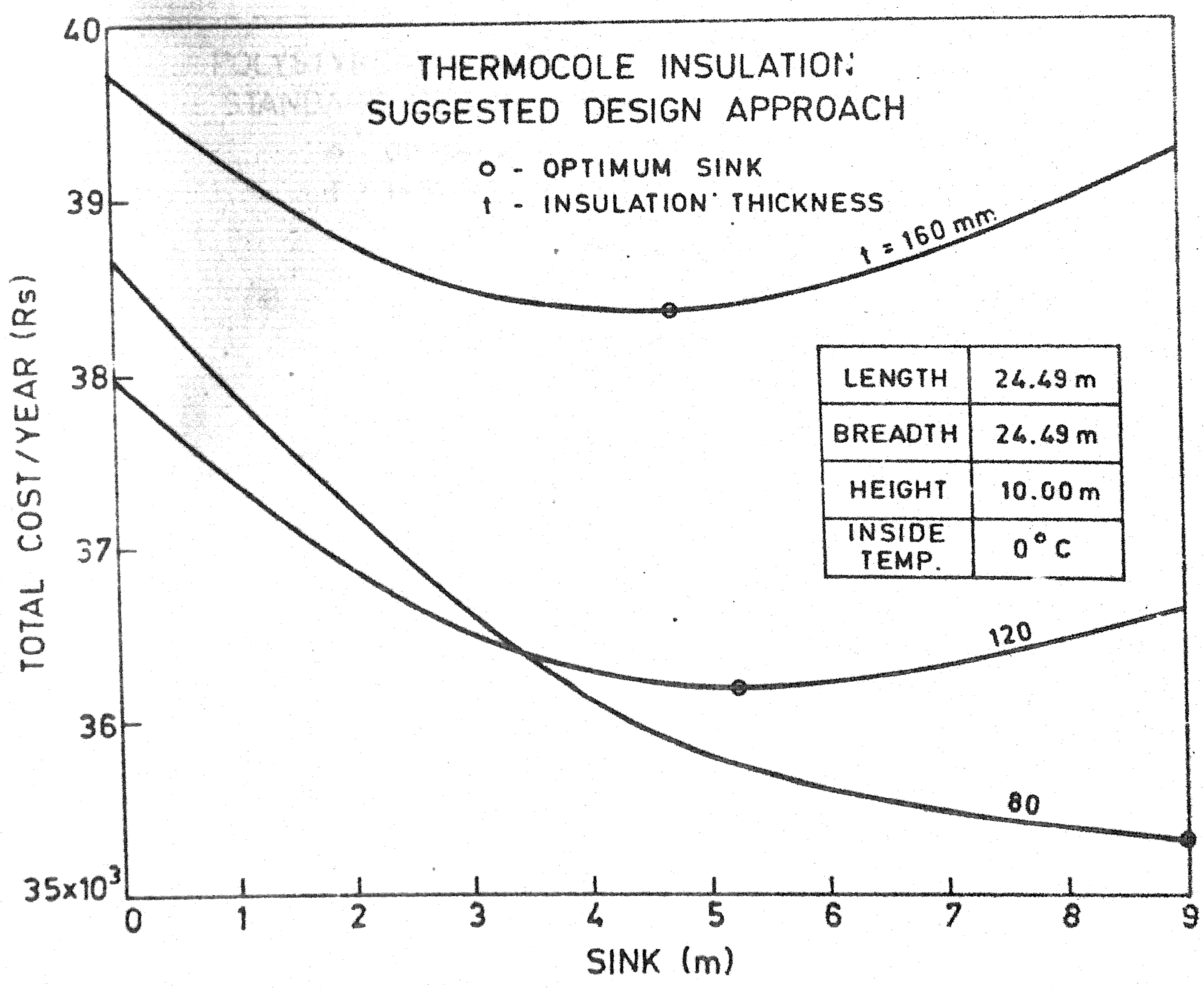


FIG. 4.15 VARIATION OF TOTAL COST WITH SINK.

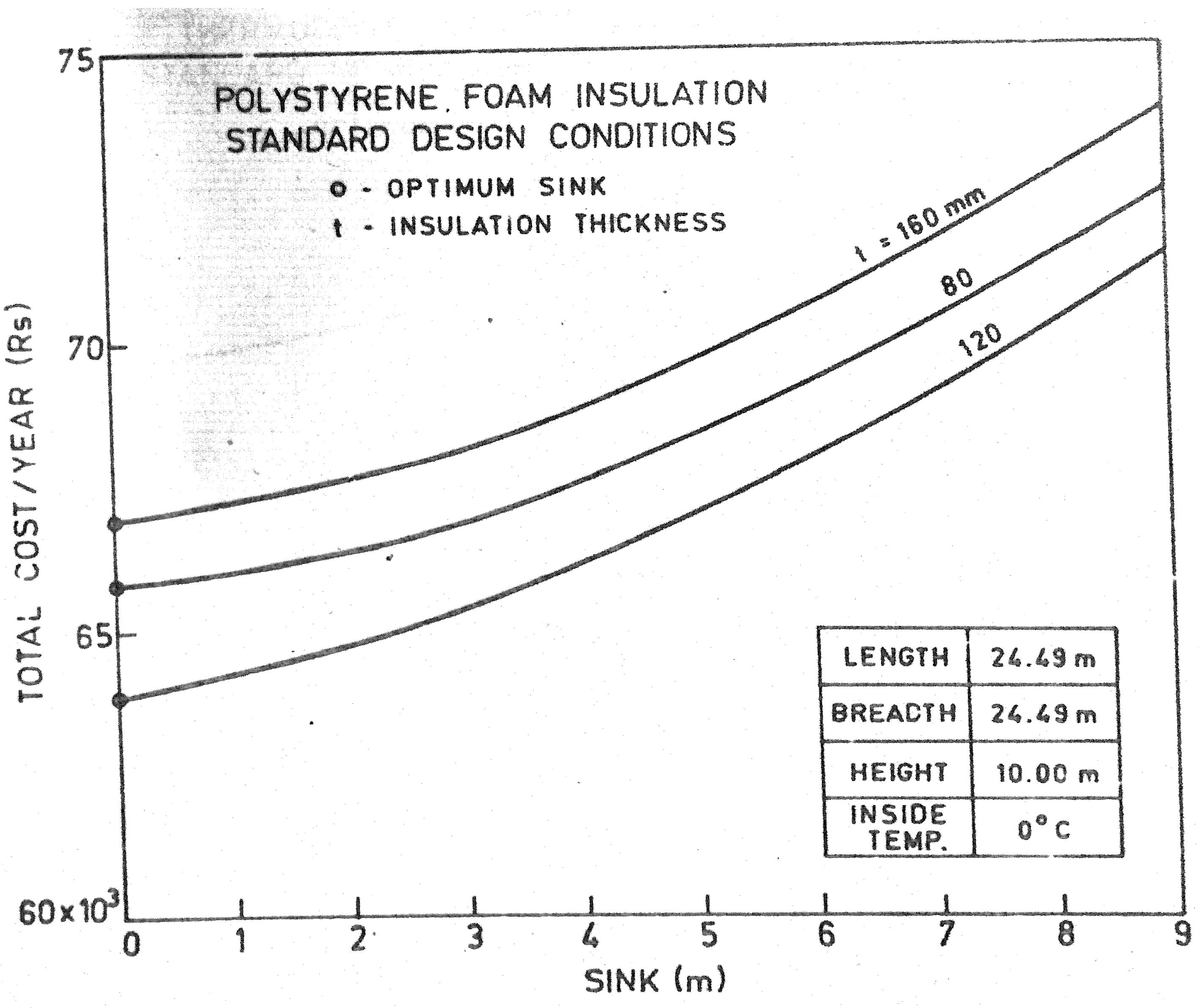


FIG. 4.16 VARIATION OF TOTAL COST WITH SINK.

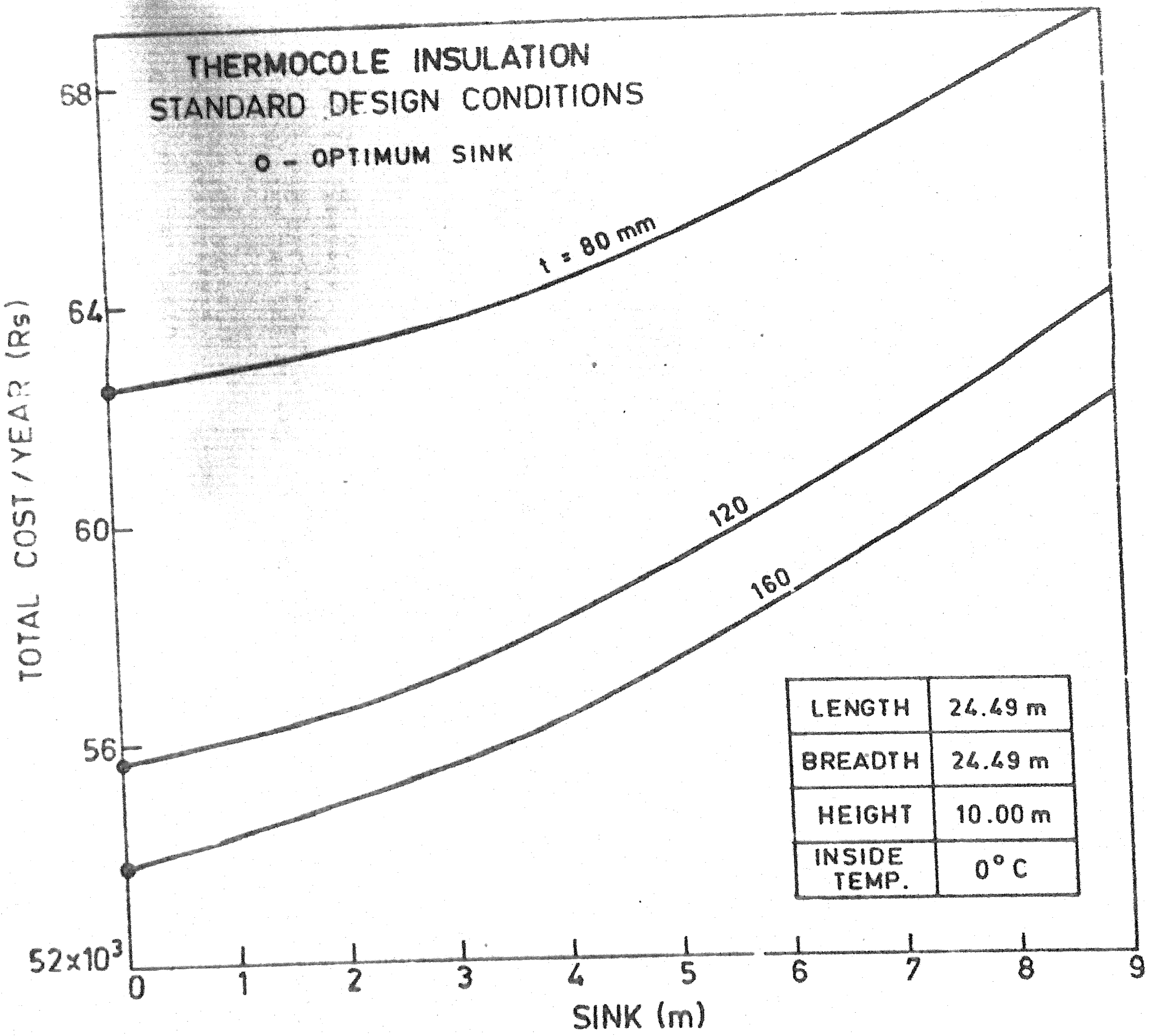


FIG. 4.17 VARIATION IN TOTAL COST WITH SINK.

PROGRAM LISTING
****

MAIN PROGRAM
****

INITIALIZATION OF DESIGN VECTOR
PRINTS OUT FINAL(OPTIMUM)DESIGN VECTOR AND TOTAL COST

SUBROUTINE INTPEN
****

CONVERTS THE ORIGINAL CONSTRAINED PROBLEM INTO
UNCONSTRAINED ONE.

SUBROUTINE POWELL
****

CONSTRAINED MINIMIZATION.
GENERATES THE PATTERN DIRECTION.

SUBROUTINE QFIT
****

ONE DIMENSIONAL MINIMIZATION BY QUADRATIC INTERPOLATION.

SUBROUTINE FUN
****

EVALUATES THE DIFFERENT INDIVIDUAL COSTS
COMPUTES THE OBJECTIVE FUNCTION
CONSTRAINTS ARE IMPOSED ON DESIGN VARIABLES.

SUBROUTINE COPF
****

EVALUATES THE COEFFICIENT OF PERFORMANCE OF SYSTEM.
COP IS USED IN CALCULATING POWER COST.

FUNCTION CP-EC

EMPIRICAL RELATIONS FOR THE PROPERTIES OF THE REFRIGERANT.

SUBROUTINE QVAL
****

READS THE DATA FILE
CALCULATES THE DESIGN AND ACTUAL COOLING LOAD.

SUBROUTINE SOLARD
****

COMPUTES THE VARIOUS SOLAR ANGLES.

SUBROUTINE HCOFTD
****

COMPUTES THE INSIDE HEAT TRANSFER COEFFICIENT.

****

```
C       *****************************************************************
C       *
C       *    COMPUTATIONS FOR OPTIMUM PARAMETERS OF A COLD STORAGE
C       *
C       *****************************************************************
C       *****************************************************************
C       * THIS PROGRAM GIVES THE OPTIMUM INSULATION THICKNESS ABOVE
C       * GROUND LEVEL AND ON THE CEILING,OPTIMUM LENGTH AND BREADTH
C       * FOR A GIVEN VOLUME.THE HEIGHT IS DEPENDANT ON THE LENGTH
C       * AND BREADTH FOR A GIVEN VOLUME.IT ALSO GIVES OPTIMUM SINK
C       *****************************************************************
C
C       THIS PROGRAM WAS DEVELOPED BY P.L.VENKATESH AT I.I.T KANPUR
C       ON 9/10/84 FOR THE M.TECH  THESIS.
!!
!!      The Main Program
C
!!      X(1)=INSULATION THICKNESS(ABOVE GROUND LEVEL)
!!      X(2)=INSULATION THICKNESS(ON CEILING)
!!      X(3)=SINK
!!      X(4)=LENGTH
!!      X(5)=BREADTH
C
        DIMENSION X(50)
        COMMON/GRP1/RO,EPSLON,DELT1
        COMMON N
        COMMON/PP6/FI
        DATA EPSLON,DELTA/-.01,1000000.0/
        RO=ABS(EPSLON*DELTA)
        DELT1=DELTA
        N=5
        X(1)=0.06   !! THESE ARE THE INITIAL VALUES OF THE DESIGN VE
        X(2)=0.08
        X(3)=0.1
        X(4)=19.0
        X(5)=19.0
        TYPE 2
2       FORMAT(//,3X,'THE STARTING POINT DESIGN VECTORS')
        TYPE 1,(X(I),I=1,N)
1       FORMAT(///,3X,8E15.6)
        CALL INTPEN(X,FM,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT
       1COST3,COST5,C1,C2,C3,C4,C5,TC)
        TYPE 608
608     FORMAT(//,3X,'THE REQUIRED CONVERGENCE HAS BEEN
       1 ACHIEVED',//,3X,'THE FINAL DESIGN VECTOR :')
        TYPE 23,(X(I),I=1,N)
23      FORMAT(/3X,'OPTIMUM INSULATION ABOVE GL =',F10.5//3X,'OPTIMU
       1 INSULATION THICKNESS ON ROOF =',F10.5//3X,'OPTIMUM SINK ='
       2,F5.3//3X,'OPTIMUM LENGTH =',F5.2//3X,'OPTIMUM BREADTH =',
       3F5.2//)
        TYPE 24,FM
24      FORMAT(/,3X,'F - MINIMUM = ',E15.6)
        TYPE 25,FI
25      FORMAT(/,3X,'THE MINIMUM VALUE OF THE FUNCTION:',F10.4)
        TYPE 6005,COP,COST1,COST2,COST3,COST5,HEIGHT,SINK,TINS1,C1,
       1C2,C3,C4,C5,TC,QDES,QTOT
6005    FORMAT(//10X,'COP=',F8.3/10X,'COST OF INSULATION/CUBMET=',F8
       1/10X,'POWER CHARGES/KW-H =',F8.4/10X,'MACHINERY COST/TON=',
       2F11.2/10X,'DIGGING COST/CUBMET=',F10.3/10X,'HEIGHT=',F6.2
       3/10X,'SINK=',F6.2/10X,'INSULATION THICKNESS BELOW GROUND LE
       4=',F6.4/10X,'INSULATION COST=',F10.2/10X,'RUNNING COST=',F1
       5/10X,'MACHINERY COST=',F10.2/10X,'MAINTENANCE COST=',F10.2
       6/10X,'DIGGING COST=',F10.2/10X,'TOTAL COST=',F10.2/10X,
       7'DESIGN HEAT LOAD=',F15.4/10X,'ACTUAL HEAT LOAD=',F15.4)
        STOP
        END
!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!! The subroutine for the interior penalty function!!
!! method                                          !!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!
        SUBROUTINE INTPEN(X,FM,COP,COST1,COST2,HEIGHT,SINK,TINS1,
       1 QDES,QTOT,COST3,COST5,C1,C2,C3,C4,C5,TC)
        COMMON N
        COMMON/GRP1/RO,EPSLON,DELT1
        COMMON/T2/ALPHA/SUN/S/T/OD/PP6/FI/BORDF/GJ,
       1CCOST2/PP4/GJSUM
        DIMENSION X(50),OD(50),S(50),GJ(400)
        INDEX=1
        CONV=0.001
        ALPHA=0.0
        DO 10 I=1,N
        S(I)=0.0
        OD(I)=X(I)
        CALL FUN(X,F,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,COS
       1COST5,C1,C2,C3,C4,C5,TC)
```

```
20      CALL POWEL(X,FM,CUP,CUST1,CUST2,HEIGHT,SINK,TINS1,QDES,QTOT,COST3.
       1COST5,C1,C2,C3,C4,C5,TC)
        IF(INDEX.EQ.1)GO TO 70
        IF(ABS(FI-FI).LT.10.0)GO TO 61
        GO TO 62
61      IF(IRM.GE.8)RETURN
62      CONTINUE
70      FI=FI
        INDEX=2
82      RO=0.1*RO
        EPSLON=-RO/DELT1
        F=FM
        IRM=IRM+1
50      CONTINUE
100     RETURN
506     CONTINUE
        RETURN
        END
!!
!!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!! The subroutine for Powel's methd of unconstrained!!
!! minimization                                      !!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!
        SUBROUTINE POWEL(X,FMIN,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES
       1,QTOT,COST3,COST5,C1,C2,C3,C4,C5,TC)
        COMMON/SUM/S
        COMMON N
        COMMON/PP6/FI/BURDE/GJ,NCNSTR/PP4/GJSUM
        DIMENSION GJ(400),X(50),SQ(50,51),S(50),D0(50)
!!
!!
!! Initialization of SQ to be the coordinate
!! unit vectors
!!
        N1=N+1
        CONV=0.001
        DO 10 I=1,N
        DO 10 J=1,N
        SQ(I,J)=0.0
10      IF(I.EQ.J) SQ(I,J)=1.0
!!
!!
!! To store D at DO
!!
        INDEX=1
80      DO 20 IB=1,N
20      DO(IB)=X(IB)
        IQ=1
120     IF(IQ-N)1,1,2
1       DO 30 IC=1,N
30      S(IC)=SQ(IC,IQ)
        CALL QFIT(X,FMIN,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
       1COST3,COST5,C1,C2,C3,C4,C5,TC)
        IQ=IQ+1
90      F=FMIN
        GO TO 120
!!
!!
!! To generate the pattern direction
!!
2       DO 40 IP=1,N
40      SQ(IP,N1)=X(IP)-DO(IP)
        DO 41 IP=1,N
        IF(SQ(IP,N1).NE.0.0)GO TO 42
41      CONTINUE
        GO TO 100
42      SUM=0.0
        DO 50 IZ=1,N
50      SUM=SUM+SQ(IZ,N1)**2
        DO 60 IY=1,N
        SQ(IY,N1)=SQ(IY,N1)/SQRT(SUM)
60      S(IY)=SQ(IY,N1)
        CALL QFIT(X,FMIN,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
       1COST3,COST5,C1,C2,C3,C4,C5,TC)
        DO 70 IP=1,N
        DO 70 JP=1,N
70      SQ(IP,JP)=SQ(IP,JP+1)
        IF(INDEX.EQ.1)GO TO 81
        IF(ABS((FMIN-F)/F).LT.0.01)GO TO 110
81      INDEX=INDEX+1
        F=FMIN
        GO TO 80
110     CONTINUE
100     CONTINUE
        RETURN
```

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!! The subroutine for one dimensional minimization !!
!! by quadratic interpolation                       !!
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
!!
      SUBROUTINE QFIT(X,F,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES
     1,QTOT,COST3,COST5,C1,C2,C3,C4,C5,TC)
      DIMENSION X(50),OD(50),S(50)
      COMMON/T2/ALPHA
      COMMON/T/OD
      COMMON/RIN/ALQST
      COMMON N
      COMMON/SUB/S
      ALPHA=0.0
      INDEX=1
80    CONTINUE
      IQ=1
      DO 10 I=1,N
10    OD(I)=X(I)
      DX=0.1
      DXI=DX
      IF(INDEX.EQ.1)GO TO 78
79    ALPHA=ALST
78    AL1=ALPHA
      CALL FUN(X,FAL1,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
     1COST3,COST5,C1,C2,C3,C4,C5,TC)
      F1=FAL1
77    ALPHA=ALPHA+DX
      I=0
      CALL FUN(X,FRE,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
     1COST3,COST5,C1,C2,C3,C4,C5,TC)
      IF(F1.LT.FRE)GO TO 11
      F2=FRE
      AL2=ALPHA
33    DX=3.0*DX
      ALPHA=ALPHA+DX
      CALL FUN(X,FRE,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
     1COST3,COST5,C1,C2,C3,C4,C5,TC)
      IF(FRE.LT.F2)GO TO 22
      F3=FRE
      AL3=ALPHA
      GO TO 66
22    F2=FRE
      AL2=ALPHA
      GO TO 33
11    F3=FRE
      DX=DX/2.0
      AL3=ALPHA
      ALPHA=ALPHA-DX
      CALL FUN(X,FRE,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
     1COST3,COST5,C1,C2,C3,C4,C5,TC)
      I=I+1
      IF(DX.LT.0.0)GO TO 88
      SF3=FRE
      SAL3=ALPHA
      GO TO 99
88    SF2=FRE
      SAL2=ALPHA
      IF(I.GT.5.AND.DX.LT.0.0.AND.
     1FRE.GT.F1)GO TO 111
99    IF(I.GT.5.AND.FRE.GT.F1) DX=-DXI
      IF(I.GT.5.AND.FRE.GT.F1) GO TO 77
      IF(F1.LT.FRE)GO TO 11
      F2=FRE
      AL2=ALPHA
      GO TO 66
111   F2=FAL1
      AL2=AL1
      F3=SF3
      AL3=SAL3
      F1=SF2
      AL1=SAL2
66    AA=(AL3-AL1)*(AL3-AL2)*(AL2-AL1)
      IF(ABS(AA).LT.1.0E-20) GO TO 45
      C=((F3-F1)*(AL2-AL1)-(F2-F1)*(AL3-AL1))/AA
      IF(C.EQ.0.0)GO TO 45
      B=(F2-F1)/(AL2-AL1)-C*(AL2+AL1)
      A=F1-B*AL1-C*AL1*AL1
      ALST=-B/(2.0*C)
      FRE=A+B*ALST+C*ALST*ALST
      ALPHA=ALST
      IQ=IQ+1
      INDEX=INDEX+1
      CALL FUN(X,FM,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
     1COST3,COST5,C1,C2,C3,C4,C5,TC)
      Q=ABS((FRE-FM)/FM)
```

```
              .GT.AL2)GO TO 55
          IF(FM.GT.F2)GO TO 133
          AL3=AL2
          AL2=ALST
          F3=F2
          F2=FM
          GO TO 66
55        IF(FM.GT.F2)GO TO 122
          AL1=AL2
          AL2=ALST
          F1=F2
          F2=FM
          GO TO 66
122       AL3=ALST
          F3=FM
          GO TO 66
133       AL1=ALST
          F1=FM
          GO TO 66
12        IF(ALST.LT.AL2)GO TO 13
          IF(FM.GT.F2) GO TO 14
          AL3=AL2
          AL2=ALST
          F3=F2
          F2=FM
          GO TO 66
14        F1=FM
          AL1=ALST
          GO TO 66
13        IF(FM.GT.F2)GO TO 15
          AL1=AL2
          F1=F2
          AL2=ALST
          F2=FM
          GO TO 66
15        F3=FM
          AL3=ALST
          GO TO 66
44        ALPHA=ALST
          ALOST=ALPHA
          F=FM
          RETURN
45        F=F2
100       CONTINUE
          RETURN
          END
!!
!!
!! The subroutine for evaluating the function value
!!
!!
          SUBROUTINE FUN(X,F,COP,COST1,COST2,HEIGHT,SINK,TINS1,QDES,QTOT,
         1COST3,COST5,C1,C2,C3,C4,C5,TC)
          real length
          COMMON N
          COMMON/PP6/FI/BORDE/GJ,NCNSTR
          COMMON/GRP1/RO,EPSLON,DELT1
          COMMON/PP4/GJSUM/T/OD/SUN/S/T2/ALPHA
          DIMENSION X(50),S(50),GJ(400),OD(50)
          DO 1 I=1,N
1         X(I)=OD(I)+ALPHA*S(I)
          CALL COPF(COP)
          CALL ELEC(COST2)
C
          X1=X(1)
          X2=X(2)
          X2D=0.75*X(1)
          X3=X(3)
          X4=X(4)
          X5=X(5)
          X6=6000.0/(X4*X5)
          HEIGHT=X6;TINS=X(1);TINSR=X(2);TINS1=0.75*X(1);SINK=X(3)
          LENGTH=X(4);BREADT=X(5)
          CALL QVAL(X1,X2,X2D,X3,X4,X5,X6,QDES,QTOT)

          COST1=2000.0 !! COST1 IS THE INSULATION COST RS/CUBMET
          COST3=5000.0  !! COST3 IS COST OF REFRIGERATING MACHINERY RS/TON
          COST5=30.0    !! COST5 IS THE COST OF UNDERGROUND CONSTRUCTTION
          FF=0.75       !! FF IS THE FACTOR FOR ACTUAL POWER CONSUMPTION
          SF=1.2        !! SF IS THE DESIGN SAFETY FACTOR
          R=0.10        !! R IS THE RATE OF INTEREST
          L=20          !! L IS THE LIFE OF THE PROJECT
          AL=L
          PWF=((1.0+R)**L-1.0)/(R*(1.0+R)**(L-1.0)) !!PWF=PRESENT WORTH
          C1=COST1*(2.0*TINS*(HEIGHT-SINK)*(LENGTH+BREADT)+2.0*SINK*TINS1*
         1(LENGTH+BREADT)+LENGTH*BREADT*TINSR
         2+TINS1*LENGTH*BREADT)/AL
```

```
      C4=0.1*C3*PWF
      C5=COST5*LENGTH*BREADT*SINK*1.2/AL
C     ****************************************************************
      FI=C1+C2+C3+C4+C5   !! FI IS THE OBJECTIVE-TOTAL COST
      TC=FI
C     ****************************************************************
      GJ(1)=0.05/X(1)-1.0    !! INSULATION THICKNESS ABOVE GL(UB)
      GJ(2)=X(1)/0.15-1.0    !! INSULATION THICKNESS ABOVE GL(LB)
      GJ(3)=0.07/X(2)-1.0    !! INSULATION THICKNESS ON ROOF (LB)
      GJ(4)=X(2)/0.20-1.0    !! INSULATION THICKNESS ON ROOF (UB)
      GJ(5)=-X(3)   !! SINK (LB)
      GJ(6)=X(3)-8.0   !! SINK (UB)
      GJ(7)=18.0/X(4)-1.0   !! LENGTH (LB)
      GJ(8)=X(4)/30.0-1.0    !! LENGTH (UB)
      GJ(9)=18.0/X(5)-1.0   !! BREADTH (LB)
      GJ(10)=X(5)/30.0-1.0   !! BREADTH (UB)
C     ****************************************************************
      NCNSTR=10
      GJSUM=0.0
      DO 310 I=1,NCNSTR
      IF(GJ(I).GT.EPSLON)GO TO 305
      GJSUM=GJSUM+1.0/GJ(I)
      GO TO 310
305   GJSUM=GJSUM+(2.0*EPSLON-GJ(I))/EPSLON**2
310   CONTINUE
      F=FI-RO*GJSUM
      RETURN
      END
C     ****************************************************************
      SUBROUTINE COPF(COP)
C     ****************************************************************
      TC=42.0;TE=-8.0;TUC=5.0;TSH=5.0;EFFC=0.85
C     ----------------------------------------------------------------
C     THIS PART CALCULATES THE COP FOR CONVERTING KW-HRS TO TON-HRS.
C     ----------------------------------------------------------------
      T1=TE
      T5=TE
      T1D=TE+TSH
      T3=TC
      T4D=TC
      T4=T4D-TUC
      P=PR(TC+273.15)/PR(TE+273.15)
      H1=HG(T1)
      H1D=H1+CP(T1)*(T1D-T1)
      S1=SG(T1)
      S1D=S1+CP(T1)*ALOG((T1D+273.0)/(T1+273.0))
      S2D=S1D
      S3=SG(T3)
      T2D=(EXP((S2D-S3)/CP(T3)))*(T3+273.0)
      T2D=T2D-273.0
      H2D=HG(T3)+CP(T3)*(T2D-T3)
      H2=(H2D-H1D)/EC(P)+H1D
      H4D=HF(T4D)
      H4=HF(T4)
      H5=H4
      COP=(H1-H5)/(H2-H1D)
      RETURN
      END
C     ****************************************************************
      SUBROUTINE ELEC(COST2)
C     ****************************************************************
C
      DIMENSION CE(20)
C     THIS PART CALCULATES THE EFFECTIVE ELECTRICITY(POWER) COST.
C     ----------------------------------------------------------------
      R=0.10
      DO 200 I=1,20
          CE(I)=1.293/(0.97986+EXP(-0.09338*I))
200   CONTINUE
      L=20
      AL=L
      CEFTVE=0.0
      DO 300 I=1,L
      CEFTVE=CEFTVE+CE(I)/(1.0+R)**(I-1)
300   CONTINUE
      COST2=CEFTVE/AL
      RETURN
      END
C     ****************************************************
C     EMPIRICAL FUNCTIONS FOR PROPERTIES OF AMMONIA
C     ****************************************************
      FUNCTION CP(T)
      IF(T.LT.10.0)GO TO 10
      CP=2.643+0.004643*(T-10.0+0.05015*(T-10.0)**2)
      RETURN
10    CP=2.1375+0.00396916*(T+45.0+0.000600638*(T+45.0)**2)
      RETURN
```

```
      FUNCTION HF(T)
      A=T/100.0
      HF=130.885+462.25*A+28.7168*A*A+13.836*A**3+5.36214*A**4
      RETURN
      END
C
      FUNCTION HG(T)
      A=T/100.0
      HG=1443.36+111.051*A-85.6543*A**2-32.7365*A**3+11.9649*A
     1**4
      RETURN
      END
C
      FUNCTION SF(T)
      A=T/100.0
      SF=0.712406+1.68522*A-0.22175*A**2+0.0763988*A**3+0.02346
     1027*A**4
      RETURN
      END
C
      FUNCTION SG(T)
      SG=SF(T)+(HG(T)-HF(T))/(T+273.0)
      RETURN
      END
C
      FUNCTION PR(T)
      TCRIT=405.50
      PCRIT=113.53
      A=19.66
      B=-15.549930
      C=-11.07219
      D=9.114107
      E=-2.152941
      F=1.81269
10    RL=A+B*(T/TCRIT)+C/(T/TCRIT)+D*((T/TCRIT)**2)+E*((T/TCRIT)**3)
     1+F*((1.0-T/TCRIT)**1.5)/(T/TCRIT)
      PR=PCRIT*EXP(RL)
      RETURN
      END
C
      FUNCTION EC(R)
      EC=0.976695-0.0366432*R+0.001337988*R**2
      RETURN
      END
C     ***********************************************************
C     ****************************************************************
      SUBROUTINE QVAL(TINS,TINSR,TINS1,SINK,LENGTH,BREADT,HEIGHT,QDES
     1,QTOT)
C     ****************************************************************
      INTEGER ORIENT,TIME(24)
      REAL IRAD(24),INE(24),INW(24),INS(24),INN(24),INR(24)
      DIMENSION TEMP(24),SOLE(24),SOLW(24),SOLN(24),SOLS(24),SOLR(24)
      DIMENSION T(6),QINF(24),TQINF(24)
      REAL KINS,K(6),LENGTH,MAXIMP,NCH,IDIFF(24)
C     ----------------------------------------------------------
      OPEN(UNIT=22,FILE='NAK.DAT')
C     ----------------INPUT STARTS-------------------------------
      READ(22,*),ALAT,MONTH
      READ(22,*),TI,UT,PHI
      READ(22,*),NLAYER
      READ(22,*),(T(I),K(I),I=1,NLAYER)
      READ(22,*),KINS
      DO 555 I=1,24
      READ(22,*),TEMP(I),IRAD(I),IDIFF(I)
555   CONTINUE
      READ(22,*),VEL,ABSPTY
      T1=TINS;T2=TINS1;T3=TINSR
C     ------------------INPUT ENDS-------------------------------
             HO=26.55+5.0663*VEL
      HOR=28.64+6.364*VEL
      ALAT=ALAT*3.1417/180.0
      HRANGL=90.0
20    DO 5000 I=1,24
      HRAN=HRANGL
      HRRAD=HRANGL*3.1415926/180.0
      TIME(I)=I
      IF(TIME(I).GE.6.AND.TIME(I).LE.18) GO TO 25
      INE(I)=0.0
      INW(I)=0.0
      INN(I)=0.0
      INS(I)=0.0
      INR(I)=0.0
      GO TO 175
25    CALL SOLARD(ALAT,HRRAD,MONTH,BETA,GAMA)
C     ----------------------SOUTH----------------------------------
      ALPHAS=ABS(GAMA)
      IF(ALPHAS.GE.(3.1415926/2.0))GO TO 12
```

```
12        COSTHS=0.0
22        INS(I)=(IRAD(I)+IDIFF(I))*COSTHS
C         -----------------------EAST------------------------------
          IF(TIME(I).GT.12)GO TO 34
          ALPHAE=ABS(GAMA-3.1415926/2.0)
          GO TO 36
34        ALPHAE=ABS(GAMA+3.1415926/2.0)
36        IF(ALPHAE.GE.(3.1415926/2.0))GO TO 32
          COSTHE=COS(BETA)*COS(ALPHAE)
          GO TO 33
32        COSTHE=0.0
33        INE(I)=(IRAD(I)+IDIFF(I))*COSTHE
C         -----------------------NORTH-----------------------------
          IF(TIME(I).GT.12)GO TO 46
          ALPHAN=ABS(GAMA-3.1415926)
          GO TO 47
46        ALPHAN=ABS(GAMA+3.1415926)
47        IF(ALPHAN.GE.(3.1415926/2.0))GO TO 42
          COSTHN=COS(BETA)*COS(ALPHAN)
          GO TO 43
42        COSTHN=0.0
43        INN(I)=(IRAD(I)+IDIFF(I))*COSTHN
C         -----------------------WEST------------------------------
          IF(TIME(I).LT.12)GO TO 52
          ALPHAW=ABS(GAMA-3.1415926/2.0)
          GO TO 56
52        ALPHAW=ABS(GAMA+3.1415926/2.0)
56        IF(ALPHAW.GE.(3.1415926/2.0))GO TO 57
          COSTHW=COS(BETA)*COS(ALPHAW)
          GO TO 55
57        COSTHW=0.0
55        INW(I)=(IRAD(I)+IDIFF(I))*COSTHW
C         -----------------------ROOF------------------------------
          INR(I)=(IRAD(I)+IDIFF(I))*SIN(BETA)
C         ---------------------------------------------------------
          IF(TIME(I).LT.12)GO TO 83
          HRANGL=HRANGL+15.0
          GO TO 171
83        HRANGL=HRANGL-15.0
171       BETAD=BETA*180.0/3.1415926
          GAMAD=GAMA*180.0/3.1415926
175       SOLE(I)=TEMP(I)+ABSPTY*INE(I)/HO
          SOLS(I)=TEMP(I)+ABSPTY*INS(I)/HO
          SOLN(I)=TEMP(I)+ABSPTY*INN(I)/HO
          SOLW(I)=TEMP(I)+ABSPTY*INW(I)/HO
          SOLR(I)=TEMP(I)+ABSPTY*INR(I)/HOR
C         ----------------------------------------------------------
C         ------------CALCULATION OF SOL-AIR TEMP ENDS--------------
C         ----------------------------------------------------------
5000      CONTINUE
C         ----------------------------------------------------------
C         SUMMATION OF AMBIENT AND(SOLAIR TEMP-AMB TEMP) STARTS
C         HERE THE TEMPS ARE SUMMED UP FROM 10 HOURS TO 15 HOURS.
C         ----------------------------------------------------------
          SIGTA=0.0
          DO 315 I=10,15
          SIGTA=SIGTA+(TEMP(I)-TI)
315       CONTINUE
          SIGTS=0.0
          DO 316 I=10,15
          SIGTS=SIGTS+(SOLS(I)-TEMP(I))
316       CONTINUE
          SIGTE=0.0
          DO 317 I=10,15
          SIGTE=SIGTE+(SOLE(I)-TEMP(I))
317       CONTINUE
          SIGTW=0.0
          DO 318 I=10,15
          SIGTW=SIGTW+(SOLW(I)-TEMP(I))
318       CONTINUE
          SIGTR=0.0
          DO 319 I=10,15
          SIGTR=SIGTR+(SOLR(I)-TEMP(I))
319       CONTINUE
          TSIGTA=0.0
          DO 1315 I=1,24
          TSIGTA=TSIGTA+(TEMP(I)-TI)
1315      CONTINUE
          TSIGTS=0.0
          DO 1316 I=1,24
          TSIGTS=TSIGTS+(SOLS(I)-TEMP(I))
1316      CONTINUE
          TSIGTE=0.0
          DO 1317 I=1,24
          TSIGTE=TSIGTE+(SOLE(I)-TEMP(I))
1317      CONTINUE
          TSIGTW=0.0
```

```
1318  CONTINUE
      TSIGTR=0.0
      DO 1319 I=1,24
      TSIGTR=TSIGTR+(SOLR(I)-TEMP(I))
1319  CONTINUE
C     ---------------SUMMATION ENDS--------------------------------
C     -------------------------------------------------------------
C     THRST STANDS FOR THERMAL RESISTANCE.
      THRST=0.0
      DO 351 I=1,NLAYER
      THRST=THRST+T(I)/K(I)
351   CONTINUE
      MAXTMP=TEMP(15)
C     MAXTMP=MAX(TEMP(14),TEMP(15),TEMP(16))
      A=LENGTH
      B=BREADT
      H=HEIGHT
      S=SINK
C     CALCULATION OF INFILTERATION LOAD.
      CP=1.0053
1112  QINFT=0.0
C
      V=A*B*(H-S)
      NCH=110.08-54.8906*ALOG(V)+11.426*(ALOG(V)**2)-1.132*(ALOG(V)**3
     1)+0.043708*(ALOG(V)**4)
      DO 937 I=10,15
      AA=1.152E-5
      BB=4.787E-9
      C=TEMP(I)+273.15
      D=647.31/C
      E=(C-210.0)**2
      PS=221.228/EXP((7.21379+(AA-BB*C)*E)*(D-1.0))
      PV=PHI*PS
      VA=29.27*C*9.8066/((1.0132-PV)*1.0E5)
      QINF(I)=A*B*(H-S)*NCH*CP*(TEMP(I)-TI)/(VA*24.0)
      QINFT=QINF(I)+QINFT
937   CONTINUE
11112 TQINFT=0.0
C
      V=A*B*(H-S)
      NCH=110.08-54.8906*ALOG(V)+11.426*(ALOG(V)**2)-1.132*(ALOG(V)**3
     1)+0.043708*(ALOG(V)**4)
      DO 1937 I=1,24
      AA=1.152E-5
      BB=4.787E-9
      C=TEMP(I)+273.15
      D=647.31/C
      E=(C-210.0)**2
      PS=221.228/EXP((7.21379+(AA-BB*C)*E)*(D-1.0))
      PV=PHI*PS
      VA=29.27*C*9.8066/((1.0132-PV)*1.0E5)
      TQINF(I)=A*B*(H-S)*NCH*CP*(TEMP(I)-TI)/(VA*24.0)
      TQINFT=TQINF(I)+TQINFT
1937  CONTINUE
C     -------------------------------------------------------------
C
1111  CALL HCOFTD(TI,MAXTMP,THRST,TINS,KINS,HO,U)
      CALL HCOFTD(TI,MAXTMP,THRST,TINSR,KINS,HO,UR)
      U1=1.0/(1.0/2.0+1.0/HO+THRST+TINS1/KINS)
      Q1=U*A*(H-S)*(SIGTA*2.0+SIGTS)+U*B*(H-S)*(2.0*SIGTA+SIGTE+SIGTW)
     1+UR*A*B*(SIGTA+SIGTR)
      Q2=U1*2.0*S*(UT-TI)*(A+B)*5.0
      QDES=Q1+Q2+QINFT
      Q3=U*A*(H-S)*(TSIGTA*2.0+TSIGTS)+U*B*(H-S)*(2.0*TSIGTA+TSIGTE+
     1+TSIGTW)+UR*A*B*(TSIGTA+TSIGTR)
      Q4=U1*2.0*S*(UT-TI)*(A+B)*24.0
      QTOT=Q3+Q4+TQINFT
999   RETURN
      END
C     -------------------------------------------------------------
      SUBROUTINE SOLARD(LAT,HRAD,MON,BET,GAM)
C     -------------------------------------------------------------
      REAL LAT
      IF(MON.EQ.1)DEC=-21.483
      IF(MON.EQ.2)DEC=-13.788
      IF(MON.EQ.3)DEC=-3.7675
      IF(MON.EQ.4)DEC=7.898
      IF(MON.EQ.5)DEC=17.3975
      IF(MON.EQ.6)DEC=22.62
      IF(MON.EQ.7)DEC=21.77
      IF(MON.EQ.8)DEC=15.13
      IF(MON.EQ.9)DEC=5.4375
      IF(MON.EQ.10)DEC=-6.6325
      IF(MON.EQ.11)DEC=-17.03
      IF(MON.EQ.12)DEC=-22.65
150   DEC=DEC*3.1417/180.0
      SINBET=COS(LAT)*ABS(COS(HRAD))*COS(DEC)
```

```
      GAM=ASIN(SINGAM)
      RETURN
      END
C     -----------------------------------------------------------
C     -----------------------------------------------------------
      SUBROUTINE HCOFTD(STI,MAXT,STHRST,STINS,KIN,SHO,SU)
C     -----------------------------------------------------------
      REAL MAXT,KIN
      DELT1=0.01
2000  TWI=STI+DELT1
      HI=6.48*(DELT1**0.25)
      SU=1.0/(1.0/HI+1.0/SHO+STHRST+STINS/KIN)
      FLUX1=SU*(MAXT-STI)
      DELT2=FLUX1/HI
      PERDIF=ABS(DELT1-DELT2)*100.0/DELT1
      IF(PERDIF.LT.1.0)GO TO 1000
C      DELT1=DELT1+0.00025
      DELT1=DELT2
      GO TO 2000
1000  RETURN
      END
C     ****************************************************************
```

```
[illegible]
0.0,24.5,0.65
3
0.04,2.47,0.2,2.92,0.04,2.47
0.150
29.5,0.0,0.0
29.0,0.0,0.0
28.5,0.0,0.0
28.5,0.0,0.0
28.0,0.0,0.0
26.0,1233.54,82.66
29.0,2318.22,155.322
31.5,2764.04,185.184
33.5,2988.79,200.25
35.5,3109.82,208.37
37.0,3171.00,212.47
38.5,3189.89,213.73
39.5,3171.00,212.47
40.5,3109.82,208.37
41.5,2988.79,200.25
39.5,2764.04,185.184
39.0,2318.22,155.322
38.0,1233.54,82.66
36.0,0.0,0.0
34.5,0.0,0.0
33.5,0.0,0.0
33.0,0.0,0.0
31.5,0.0,0.0
30.0,0.0,0.0
11.5,0.75
```